TIGHT BINDING BOOK

PLATE I.—THE ROYAL OBSERVATORY, GREENWICH.
Founded by King Charles II, in the year 1675.

Frontispiece]

WORLDS WITHOUT END

BY

H. SPENCER JONES

M.A., Sc.D., F.R.S.

ASTRONOMER ROYAL

HONORARY FELLOW, JESUS COLLEGE, CAMBRIDGE

Were a star quenched on high,
  For ages would its light,
Still travelling downwards from the sky,
  Shine on our mortal sight.

LONGFELLOW.

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TO

MY FATHER

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PREFACE

In this book I have endeavoured to give a picture of the Universe and of the place that the Earth occupies in it, as revealed by astronomical observation. Being intended primarily for the general reader, the use of technical terms has been avoided and no account of the instruments and methods of observation has been included, though a general indication has been given of the manner in which some of the results have been obtained. Improvements in the design and construction of telescopes and auxiliary instruments, new methods of observation and the continued refinement of technique have each played an important part in obtaining the results which are described.

The plan that has been followed is to start at home, with our Earth and its satellite, the Moon, and then to proceed outwards into space. After a descriptive account of the members of the solar system, we look at other stars to find how one differs from another and to what extent the Sun can be regarded as a typical star. We then pass first to an account of what has been learnt about the stellar universe to which we belong, and finally to consider the other more or less similar universes with which space is populated.

These results of observation can be accepted as reasonably well established, though undoubtedly future observations will necessitate some changes being made in the details of the picture here presented.

The last two chapters are more speculative than those which precede them. The theoretical astronomer uses the material which has been provided by observation; from what is seen he attempts to infer what is unseen, from the present to infer the past and the future. These researches have proved extraordinarily fruitful in many directions. It is with some justification, for instance, that we can claim to know more about the interior of a star than about the interior of the Earth. But it is necessary to emphasise that in many respects his conclusions are neither final nor necessarily correct.

The originals of the photographs illustrating the book were made at many different observatories and by many different astronomers. The sources of the plates are as follows: Royal Observatory, Cape of Good Hope, XXI, XXII*c*, XXIX*a*; Lowell Observatory, Flagstaff, Arizona, IX*b*, XI*b*; Royal Observatory, Greenwich, I, XIII*a*, XIV*a* and *b*, XV, XXII*b*; Helwan Observatory, Egypt, XII*a* and *b*; Heidelberg Observatory, Germany, XI*a*;

Kodaikanal Observatory, India, XVI, XIX; Lick Observatory, Mount Hamilton, California, VII*a*, VIII*a* and *b*, IX*a*, XIII*b*; Meudon Observatory, France, XVII, XVIII; Mount Wilson Observatory, California, IV, XXVII*a* and *b*, XXIX*b*, XXX*c*, XXXI*b*, XXXII; Paris Observatory, II; Sproul Observatory, Swarthmore, Pennsylvania, XX*a*; Yerkes Observatory, Williams Bay, Wisconsin, III, XXII*a*, XXII*d*, XXVI*a* and *b*, XXXI*a*; Dr. F. E. Ross, XXIII, XXIV, XXV; the late Prof. E. E. Barnard, X*a*, XX*b*, XXVIII. Plates V and VI are from *The Moon*, by Nasmyth and Carpenter.

I am much indebted to the Directors of the several observatories, and to Dr. F. E. Ross, for their kind permission to reproduce these photographs.

H. SPENCER JONES.

ROYAL OBSERVATORY,
GREENWICH,
September 12th, 1935.

CHAPTER I

THE EARTH—OUR HOME

THE Greek astronomers and their followers believed the Earth to be the centre of the Universe. Around it moved the Sun, the Moon, the planets and the stars, which were supposed to be carried on the surfaces of perfectly transparent crystal spheres. The Greeks believed the order of increasing distance from the Earth to be the Moon, Mercury, Venus, the Sun, Mars, Jupiter and Saturn. The stars were supposed to be attached to an outer crystal sphere. They assumed that each of these spheres turned about a common axis in a period of one day, from east to west. In this way they were able to account for the daily rising and setting of the heavenly bodies. The dawn of modern astronomy came in the sixteenth century when the Polish astronomer Copernicus put forward in the year 1543 the revolutionary theory that instead of the Sun moving round the Earth, it was the Earth which moved round the Sun and that the daily rising and setting of the heavenly bodies was to be explained by the rotation of the Earth about its axis in a period of one day. The theory of Copernicus met with much opposition; it was seen that if it was accepted the Earth must be displaced from its proud position at the centre of the Universe. To an age which was still bound by the views put forward many centuries before by the Greek philosophers this was a real difficulty. It was at least as late as the time of Galileo, in the seventeenth cen-

tury, when confidence in the old ideas had been shaken by his discoveries of the satellites of Jupiter and by his investigations of the spots on the surface of the Sun, before the theory of Copernicus began to be widely accepted.

But gradually the new ideas prevailed. Yet it was not until the year 1851 that the rotation of the Earth was actually demonstrated by means of a famous experiment made by the French physicist Foucault. He suspended a heavy iron ball from the dome of the Panthéon in Paris by a wire more than 200 feet in length. The ball was set slowly swinging to and fro. A pin fixed to the lower side of the ball marked the surface of a tray of sand on the floor beneath the pendulum and indicated the direction in which the pendulum was swinging. If the Earth were not rotating, the pin would continue to trace the same line on the surface of the sand. But if the Earth is rotating, though the pendulum would continue to swing backwards and forwards parallel to the same plane, the tray of sand would be slowly carried round beneath it. The trace marked on the sand would then gradually change its direction. This was just what Foucault found. The experiment has often been repeated, and it can be used to demonstrate to a large audience the rotation of the Earth in the course of a few minutes.

The Earth makes one complete rotation about its axis in the course of a day. The day provides our fundamental unit of time, and we subdivide it for convenience into smaller units—hours, minutes and seconds. For the purposes of everyday life, the Earth serves as the natural timekeeper, and

by means of clocks we keep count of the subdivision into hours, minutes and seconds. The astronomer can just as easily use the Sun, the Moon or one of the planets as a clock. When he does so, he finds that there are small discordances between the time as derived from the rotation of the Earth and from, say, the motion of the Moon. Whether he uses the Moon, the Sun, Mercury or Venus as his clock, in every instance the discordances from the clock provided by the rotation of the Earth are the same. If, out of five clocks, four agree in showing the same time whilst the fifth shows a different time, the chances are very great that the fifth clock is a bad timekeeper. For such reasons, it is concluded that the Earth is not a perfect timekeeper and that the length of the day is slightly variable. From the records of ancient observations of eclipses of the Sun and the Moon, it has been concluded that during the last two thousand years the day has been gradually getting longer; the average increase in the length of the day in the course of a century is about one-thousandth of a second. In addition to this gradual but progressive increase in the length of the day, there are also irregular changes which sometimes occur with great abruptness. Thus in 1785 the rotation slowed down and in 1899 it speeded up again. During the interval from 1785 to 1899, the cumulative effect of the slowing down amounted to nearly one minute. The effect of the irregular variations in the rate of rotation may amount in the course of a year to about one second; the corresponding change in the length of the day is about three-thousandths of a second. Quantities of this smallness

are at present beyond, but only just beyond, the possibility of detection by the most accurate clocks which have yet been made. Hitherto it has been necessary for the astronomer to check his clocks by means of the rotation of the Earth; he now looks forward to the time when, as the result of still further improvement in precision clocks, he will be able to use his clocks to check the constancy of the rotation of the Earth.

The rotation of the Earth once in the course of a day may not at first sight seem rapid. Yet the rotation causes every point on the equator to travel at a speed exceeding 1,000 miles an hour, or through a distance of one mile in every $3\frac{1}{2}$ seconds. It is therefore not surprising that the rotation has an important influence on the great circulatory movements in the atmosphere and in the oceans. In a cyclonic disturbance or " depression " in the northern hemisphere, the air streams spirally inwards in an anti-clockwise direction towards the centre of the depression. In a depression in the southern hemisphere the air streams inwards in a clockwise direction. These motions, opposite in the two hemispheres, are caused by the rotation of the Earth. The north-east trade-winds in the northern hemisphere, the south-east trade-winds in the southern hemisphere as well as the anti-trades in the upper atmosphere, flowing from the south-west in the northern hemisphere and from the north-west in the southern, are all controlled by the rotation of the Earth.

The size and shape of the Earth are determined by surveying operations. The measurement of the

distance of any heavenly body is based ultimately upon a knowledge of the distance apart of two points on the surface of the Earth. Such knowledge is therefore of fundamental importance for the astronomer. The survey work depends upon the accurate measurement of an initial base-line; from each end of this base-line a distant well-defined mark, such as a church spire or a specially constructed beacon, is observed with a theodolite and its distance computed. From this mark and from one end of the base-line another mark is observed, and so on. By thus building up a chain of triangles the survey is extended, every distance which is determined depending upon the length of the initial base-line. If the survey extends over a large area, it is usual to have several base-lines in different parts of the area, to obtain increased accuracy.

By such observations extended over large areas of land in various parts of the world, it is found that the Earth is approximately spherical in shape but somewhat flattened at the poles. It is therefore shaped somewhat like a Tangerine orange. The radius measured from the north or the south pole is about 3,950 miles; in the plane of the equator the radius is about 3,963 miles, a difference of 13 miles. From these dimensions it follows that the area of the surface is nearly 200 million square miles.

The mass of the Earth is represented in tons by 6 followed by twenty-one zeros, or is 6,000 millions of millions of millions of tons. The determination of the mass of the Earth is often spoken of as "weighing the Earth." Such an expression is misleading. The weight of anything on the Earth

is the force with which the Earth attracts it. If there were no such force as gravity, the Earth would not attract it and it would therefore have no weight. The same body on the Sun would weigh about twenty-eight times as much as on the Earth, because the Sun attracts with a much greater force than the Earth. It is the quantity of matter in the Earth, or in other words its mass, which we really find when we weigh the Earth.

All the methods which have been used to weigh the Earth depend upon Newton's law of gravitation. According to this law, any two pieces of matter attract each other with a force which is proportional to the product of their masses and inversely proportional to the square of the distance between them. If, for instance, the distance is halved, the attractive force becomes four times as great; if the mass of one of the bodies is doubled, the attractive force is also doubled. It is the attraction of the Earth on an apple which causes it to fall to the ground; it is the attraction of the Sun on the Earth which causes it to move around the Sun instead of flying away into space; it is the attraction of the Moon on the waters of the oceans, tending to heap them up, which is responsible for the tides; it is the attraction of the Earth on the air which prevents the atmosphere from rapidly dissipating away into space. If a body is weighed with a pair of scales and a large massive lump of lead is then placed under the pan of the scales, the weight needed to balance the scales will be slightly increased because of the extra attraction of the mass of lead. The increase in weight provides a means of comparing

the mass of the lump of lead with the mass of the Earth; the mass of the Earth can therefore be inferred. This is the principle of the methods by which the Earth is weighed.

The mean density of the Earth is found by dividing the mass by the volume; it is about $5\frac{1}{2}$ times the density of water. In other words, the weight of the Earth is $5\frac{1}{2}$ times greater than it would be if the Earth consisted entirely of water. The surface rocks are only about three times denser than water. Volume for volume, therefore, the interior material is considerably heavier than the surface material. The higher density of the interior is no doubt due to some extent to the great pressure to which it is subjected by the weight of the overlying rocks. But this does not provide a complete explanation, and it is believed that the inner portion of the Earth is really composed of heavier materials than the outer portion.

We cannot hope to obtain much direct information about the interior of the Earth. The deepest mine-shafts go down to a depth of several thousand feet only—equivalent to a mere scratch in the surface. Near the surface the temperature increases rapidly inwards, about 1° F. for every 200 feet. It may be inferred that the interior is hot. Active volcanoes and warm springs provide direct evidence of this internal heat.

Some information about the nature of the interior can be obtained from the study of earthquake waves. An earthquake is the result of a sudden displacement of a portion of the outer solid crust of the Earth, usually occurring at some distance beneath the sur-

face. Just as plucking a violin string sets it into vibration, so the sudden displacement starts vibrations which travel outwards in all directions from the region of the disturbance. By means of sensitive instruments, called seismographs, these vibrations can be detected thousands of miles away from the earthquake. Some of the vibrations or waves travel around the surface of the Earth; others travel through the interior. The waves are of two kinds, which have been called "push" and "shake" waves. In the " push " waves the vibrations take place to and fro along the direction in which the wave travels; when an organ-pipe is sounded, the vibrations of the air in the pipe are of this type. In the " shake " waves, the vibrations take place in the direction perpendicular to that in which the wave travels; the waves on the ocean are of this type. The investigation of the way in which the various waves travel across or through the Earth, based on the records of many seismographs distributed over the Earth's surface, is difficult and complicated. From such investigations it is concluded that the Earth has a hot liquid core. The radius of this liquid core is about 2,000 miles and its density is about equal to that of iron. It is believed that it is mainly composed of metals, principally iron, with probably a certain amount of nickel. Outside the liquid core is the solid crust of heavy rocks with a density about four times that of water. The lighter surface layer, composed mainly of granitic rocks, is estimated to extend to a depth of only 40 or 50 miles.

The flattened shape of the Earth, with the bulge around the equator, has an important consequence.

We have mentioned that it is the gravitational pull of the Sun which keeps the Earth in its orbit and prevents it flying away into space. This same gravitational pull has another result; the Sun pulls the portion of the bulge which is nearest to it more strongly than the portion which is farthest from it. The Earth can be regarded as a huge gyroscopic top spinning in space. The axis of a spinning gyroscope will always point in the same direction in space unless some disturbing force causes a change. The gyroscopic compass is based on this fact; in whatever direction the ship may turn, the compass continues to point in the true north and south directions. The unequal pull of the Sun on the Earth's opposite bulges acts as such a disturbing force and causes the pole of the heavens—the point in the sky near the Pole Star to which the axis of the Earth points—to "precess" or, in other words, to move slowly round in a circle. The pole moves completely round this circle once every 25,800 years. As a consequence of this precession, the Pole Star, which is now only slightly more than one degree distant from the pole, has not always been and will not always continue to be near to the pole. About 13,000 years ago, the Pole Star was about 47° distant from the true pole, which was then not far from the bright star Vega. At present the Pole Star is slowly getting nearer to the true pole, but in a few hundred years' time it will begin to move away from it again.

It is interesting to recall that this precession or movement of the pole was discovered by the Greek astronomer Hipparchus about 125 B.C. Hipparchus determined the length of the year in two different

ways. His first method was to set up a vertical pole, called a gnomon, and to determine when the noonday shadow had its shortest length. This occurred at midsummer when the Sun was at its highest in the sky. By making observations in two successive years, the length of the year can be found, though for increased accuracy it is desirable to continue the observations over a number of years. His second method was to observe what were termed the "heliacal risings" of stars. The heliacal rising occurs when the star rises above the horizon exactly at sunrise. By recording the dates on which the heliacal risings occur in successive years, the length of the year can be obtained. Hipparchus found that the year given by the second method was about 20 minutes longer than that given by the first method, and this discordance led him to the discovery of precession.

The Moon also exerts a gravitational pull on the Earth; this pull causes a "nutation" or wobbling of the axis of the Earth about the mean position. A complete wobble to and fro takes place in about 19 years. The nutation was discovered by Bradley, as the result of a long series of observations commenced in the year 1725. The telescope used by Bradley for the observations which led him to the discovery of the wobbling of the axis of the Earth is one of the treasured possessions of the Royal Observatory, Greenwich.

The Earth is surrounded by an atmosphere of air. At the surface of the Earth dry air consists of about 78 per cent. of nitrogen, 21 per cent. of oxygen, nearly 1 per cent. of argon and smaller amounts

of carbon dioxide, hydrogen and the rare gases helium, neon, krypton and zenon. The presence of argon was discovered by Rayleigh and Ramsay in 1894; the other rare gases which are present in much smaller quantities were discovered by Ramsay shortly afterwards. It is believed that the oxygen in the atmosphere is due largely to the action of vegetation. Oxygen is chemically a very active element, eager to form compounds with other elements. The rusting of iron is due to the affinity of iron for oxygen. Combustion is caused by the combination of oxygen with carbon; our coal fires would not burn if there were no oxygen in the air. By these processes, and by many others, oxygen is continually being abstracted from the atmosphere. Under the action of sunlight the green cells in plants and the leaves of trees absorb carbon dioxide; the carbon is utilised for building up the cells of the plant and the oxygen is given out to the atmosphere. Oxygen is used up by animal life in the process of respiration and carbon dioxide is given out as a waste product. Vegetation therefore performs a valuable function in preventing the continued accumulation of the carbon dioxide and in replenishing the oxygen in the atmosphere.

The composition of the atmosphere does not change much up to a height of several miles. Within this region, the temperature decreases with height and vertical convection mixes the air and keeps the composition nearly uniform. At great heights, where this mixing does not occur, the atmosphere probably consists mainly of helium, or of helium and hydrogen, which are the two lightest elements.

The density at such heights is, however, so low that the total amount of these gases is small. Of considerable interest to the astronomer is a layer at a height of about 20 miles containing ozone. The ozone, though equivalent to a layer at the surface only one-eighth of an inch thick, absorbs strongly light of short wave-length in the far ultra-violet region of the spectrum. The light which reaches us from the Sun and the stars is therefore deficient in these wave-lengths. Though this is a handicap to the astronomer, the ozone layer is beneficial to mankind, for it protects us from the intense actinic rays which are injurious to human beings.

If the atmosphere had the same density throughout as at the surface, it would extend to a height of about 5 miles only. But as the density decreases rapidly with height, the atmosphere extends to a considerable height above the Earth's surface. Shooting stars enter the Earth's atmosphere from outside, and many become visible at heights as great as 120 miles. A shooting star must travel for a considerable distance through the rarefied upper atmosphere before it is sufficiently heated by friction to become incandescent. It seems probable, therefore, that the atmosphere extends to heights considerably greater than 120 miles.

Water-vapour plays a part of great importance in the atmosphere. It is present only in the lower layers, clouds rarely being found at heights greater than about 6 miles. If the atmosphere contained no water-vapour, there would be neither clouds, dew, rain, hail, snow nor thunderstorms, and neither plant nor animal life would be possible. The water-

vapour in the atmosphere also plays a rôle of great importance in controlling the temperature of the Earth. The Earth is warmed by the heat radiation which it receives from the Sun; but the Earth also emits radiation into space. There is a general balance between the amount of heat which the Earth as a whole receives from the Sun and the amount which it, in turn, sends out into space. Actually it is not the surface of the Earth which is mainly concerned in re-emitting the radiation received from the Sun; much the greater part of it is emitted by the clouds and the water-vapour in the atmosphere.

If the heat received from the Sun were to be increased, the Earth's surface would at first become warmer, the effect at the equator being greater than at the poles. The increased difference in temperature between the equator and the poles would result in a more vigorous circulation of the atmosphere and therefore in increased windiness. As the combined result of the higher temperature of the surface and of the stronger winds, there would be greater evaporation and an increase both in cloudiness and in rainfall. The increased cloud would reflect back into space a greater proportion of the radiation from the Sun, and this would bring about a fall in temperature at the surface. It is probable that the output of radiation from the Sun is not absolutely constant, and there is some evidence in support of the view that the Earth becomes cooler when the Sun's output of heat becomes greater. Thus we have the paradox of a hot Sun and a cool Earth, due entirely to the important part played by the water-vapour

contained in the atmosphere. Another consequence of an increase in cloudiness may be mentioned. Cloudy days and cloudy summers are relatively cool, because the clouds reflect back a part of the radiation from the Sun, so that the amount which reaches the surface of the Earth is reduced. Cloudy nights and cloudy winters are relatively warm, because the escape of radiation from the Earth's surface into space is impeded. Therefore an increase in solar radiation, by causing an increase in cloudiness, tends to produce smaller extremes of temperature between summer and winter and between day and night.

The blue colour of the sky and the beautiful colour effects often seen at sunrise and sunset are due to the Earth possessing an atmosphere. In its passage through the atmosphere some of the light from the Sun is scattered in all directions by the molecules of air, but the blue light is scattered to a much greater extent than the red light. When the Sun is near the horizon, its light reaches us through a much greater thickness of atmosphere than when it is higher in the heavens; the blue light is gradually scattered sideways, leaving the light which is much richer in the colours of longer wave-length—the reds, oranges and yellows—to reach us. The blue colour of the sky arises from sunlight passing through the upper layers of the atmosphere; the scattered blue light is thrown sideways and reaches the observer. If the Earth, like the Moon, were devoid of an atmosphere, the sky would appear black and the stars would be seen shining steadily in the sky in broad daylight but never twinkling. What a para-

dise for astronomers if life were possible under such conditions!

The study of the past history of the Earth as revealed by igneous and sedimentary rocks and by fossils is the concern of the geologist rather than of the astronomer. The astronomer is, nevertheless, interested in any evidence which the geologist can provide as to the age of the Earth. Any conclusions which the astronomer may reach about the age of the Sun and of the stars in general must not be in direct conflict with the conclusions of the geologist as to the age of the Earth. It seems certain that the Earth and the other planets were formed from the Sun; the age of the Sun must necessarily therefore be greater than the age of the Earth. About 250 years ago, a former Astronomer Royal, Edmond Halley, suggested that the amount of salt in the ocean would provide a means of estimating the age of the Earth, though sufficient data for the purpose were not available to him. Every river carries down to the sea soluble salts, which have been dissolved from the soil as the rain-water percolated through it, as well as solid matter in suspension. The solid particles are deposited on the ocean bottom; the soluble matter—which is mainly common salt—remains in the sea. Thus the oceans are gradually becoming more and more salt. It has been estimated that the total amount of sodium contained in all the oceans of the globe is about 12,600 million million tons and that the total amount added by the rivers in the form of soluble salts is about 35 million tons per year. If it could be assumed that the salinity of the oceans has been increasing at a uniform rate

since they were first formed, we could conclude that the age of the Earth—which cannot be less than the age of the oceans—must be at least 360 million years.

But the assumption is certainly not correct. Geologists have shown that the Earth has experienced a succession of stages of mountain building or uplift, followed by periods of denudation during which the rivers and streams have slowly but surely acted as levelling agents, carrying solid matter from the higher regions and depositing it on the lower. Just after a period of uplift this action must have progressed at a much greater rate than near the end of such a period. It is believed by geologists that the present rate of denudation is considerably greater than the average rate during past geological history. The age of the oceans must therefore be considerably greater than 360 million years. Another argument of a somewhat similar nature is based upon the rate at which sedimentary deposits are laid down. The geological evidence indicates that the total thickness of sedimentary rocks which have been deposited since sedimentation first started is somewhere about 500,000 feet. Since the reign of Rameses II, over three thousand years ago, sediment has been deposited in Lower Egypt at the rate of one foot every five hundred years. If this represented the average rate in the past, the age of the oldest sedimentary rocks would be about 250 million years. But again this is believed to be a considerable underestimate.

Such estimates, rough approximations as they were, sufficed to prove that the estimate of the age

of the Sun, about 22 million years, made by Lord Kelvin, was seriously in error and must be discarded. But we do not need to depend now on such uncertain methods, for in the phenomenon of radioactivity physics has placed at our disposal a clock whose rate has been constant throughout past geological history. The atoms of the heaviest known elements, such as uranium, thorium and radium, are unstable and gradually disintegrate; they pass through a series of successive stages, and finally end up as lead. During these processes electrically charged atoms of helium are shot out from the complex radioactive atoms with enormous velocities of several thousands of miles per second. This radioactive disintegration proceeds at a perfectly definite rate: though it is not possible to say that any particular atom will disintegrate during the next day or year or even during the next century, we can say with certainty that in any given time a certain fraction of the atoms will have disintegrated. The premiums charged by life assurance companies are based on tables of mortality compiled from statistics of the mortality at different ages, and it can be inferred with reasonable probability that out of every 100 persons now living and, say, 44 years old, so many will die next year, so many will survive for 30 years and so on. But the mortality tables need revision from time to time to take account of the increasing expectation of life consequent upon improved social conditions, the advance in medical knowledge and other causes. The mortality tables of the radioactive atoms need no such revision. Even though the sedimentary rocks may have ex-

perienced great changes in the temperature and in the pressure to which they have been subjected since they were first deposited on the floor of the ocean, the rate of break-up of the atoms of uranium, thorium or radium which they may contain proceeds at a rate which is perfectly indifferent to all such changes. If we have some radium or radium salt, half of the atoms of radium will have disintegrated by the end of 1,580 years; in the case of uranium, 4,500 million years must elapse before half of the atoms have disintegrated; whereas for thorium 22,000 million years are required.

Although in every case the ultimate product of radioactive disintegration is lead, which is chemically indistinguishable from common lead, there is a difference in the weight of the lead. The lead produced by the break-up of uranium atoms, which we may call uranium lead, is lighter than common lead; thorium lead is heavier than common lead. If, in any uranium mineral, lead with the same weight as uranium lead is found to be present, it may reasonably be inferred to have been produced by the break-up of uranium atoms, and from the relative amounts of lead and uranium present in the mineral its age can be deduced with considerable accuracy. It has been mentioned that the disintegration of the atoms is accompanied by the production of helium ; if the helium gas is occluded within the pores of the mineral, the age of the mineral can also be inferred from the amount of helium present. But as some of the helium may have escaped, the age determined from the amount of helium gas in the rock can only be regarded as a lower limit and

as providing a general check on the age deduced from the lead content.

An upper limit to the age of the Earth can be obtained if it is assumed that the whole of the lead contained in the igneous rocks was of radioactive origin. It has been calculated that all the lead present in these rocks could have been produced in something over 3,000 million years. It is unlikely that the age of the Earth can exceed this figure, for the radioactive elements may have existed in the Sun before the Earth was born and may there have become partially transmuted into lead; so it is possible that some of the lead in the igneous rocks may not have been produced by radioactive disintegration since the Earth was formed.

It is satisfactory to find that the relative ages which had been assigned to various rocks from geological evidence are confirmed by the direct determinations of age by the radioactive method.

The oldest rocks whose ages have been definitely determined are found in Manitoba and South Dakota, the age in each instance being about 1,700 million years. To this period in the Earth's history belong the primitive marine invertebrates. In rocks with an age of about 900 million years are found the oldest known fossils. Five hundred million years ago the invertebrate animals were beginning to appear. They were followed by the age of fishes. The earliest land floras developed some 80 million years later. Some 280 million years after they appeared, the first coal measures were laid down. Then followed the age of the dinosaurs and the great flying reptiles. The primitive mammals did not appear

in the slow progress of evolution until about 60 million years ago; still more recently came the man-apes, 8 million years ago, and in the comparatively near past came man, who has existed on the Earth for only about 1 million years. The mountain systems of the Earth are of very varied ages. The Himalayas were formed comparatively recently, only 8 million years ago; the Alps are about 21 million years old, the Pyrenees about 30 million years, the Rocky Mountains 105 million years and the Appalachian Mountains about 240 million years. It therefore seems probable that the age of the Earth from the time when the crust formed is of the order of two or three thousand million years. This conclusion is supported by some rather indirect astronomical evidence.

If we suppose the history of the Earth since it was born to be written in a book, each page of which has to deal with the history of 5 million years, some four or five hundred pages would already have been written. The history of the time which has elapsed since mankind first appeared on the Earth must be summarised in the last eight lines, and to the whole of the Christian era, unless it is to receive more than its proper proportion of the space, only one letter could be given. How many more such volumes would need to be written before conditions on the Earth have changed to such an extent that man is no longer able to exist only the future can reveal. So far as any conclusions can be drawn from the results of modern astronomical investigation, it seems possible that even when 500 volumes have been written the conditions on the Earth will not differ greatly from what they are at present.

CHAPTER II

OUR NEAREST NEIGHBOUR —THE MOON

THE nearest neighbour to the Earth in space is the Moon. Its distance can be determined without any great difficulty. The method is to observe the position of the Moon relative to the stars from each of two observatories which are several thousand miles apart; observations could be made, for example, at the Greenwich and Cape of Good Hope Observatories. The distance apart of these observatories is known because the shape and dimensions of the Earth have been determined. We have thus a base-line of known length, and if the direction of the Moon is observed at the same instant from the two ends of the line, the distance of the Moon can be calculated, as in ordinary surveying operations.

The mean distance of the Moon from the Earth is about a quarter of a million miles; the distance varies within a rather wide range of about 30,000 miles. If we set out to reach the Moon by means of an aeroplane with a cruising speed of 100 miles an hour, we should take about one hundred days to reach it. A quicker method would be to be projected from the Earth with a sufficiently high speed in a large rocket, as imagined by Jules Verne in his story entitled *A Voyage to the Moon.* The rocket will rapidly slow down because the gravitational pull of the Earth is tending to draw it back the whole time. If the rocket is fired with a speed of

less than 7 miles per second, it will slow down until it comes to a stop, and it will then begin to fall back to Earth again. When the initial speed is 7 miles per second, the rocket is just able to escape from the pull of the Earth and to get out into space. This critical velocity is called the "velocity of escape." It is about fifteen times the muzzle velocity of a high-velocity shell. If we succeeded in projecting a rocket in the direction of the Moon with this velocity it would be able to reach the Moon in about 50 hours.

The Moon is a much smaller body than the Earth, for the Earth could contain fifty bodies of the size of the Moon. The discrepancy in weight is even greater than in volume, because volume for volume the Moon is not so heavy as the Earth; actually, the weight of the Earth is nearly 82 times that of the Moon. The material of which the Moon is composed is about $3\frac{1}{3}$ times heavier than water: it is therefore comparable in density with granite and the other surface rocks on the Earth. We have already seen that the outer crust of the Earth is made of much lighter material than the interior.

The force of gravity on the Moon is only about one-sixth of its value on the Earth. A high jumper who can scale 6 feet on the Earth could with the same expenditure of effort jump to a height of 36 feet on the Moon. A moderate golfer who cannot drive the ball for more than 150 yards would be delighted, if he were on the Moon, to find that he was driving it for half a mile. Golf courses on the Moon would need to be on a correspondingly longer scale than on the Earth.

PLATE II.—THE MOON, AGED $16\frac{1}{2}$ DAYS (SHORTLY AFTER FULL MOON).

The large crater in the lower portion of the photograph, with the radiating streaks, is Tycho, 54 miles across and 17,000 feet deep. It has a central peak 5,000 feet in height.

Due to this low value of gravity on the Moon, the velocity of escape from the Moon is only about $1\frac{1}{2}$ miles a second. It is thus very much easier for a fast moving body to escape from the Moon than from the Earth. One consequence is that the Moon has entirely lost its atmosphere. The Earth's atmosphere consists of billions upon billions of molecules of oxygen, nitrogen and other substances, flying backwards and forwards with very high speeds, continually colliding with one another and rebounding in different directions. The lighter the molecule, the faster it moves. At the temperature of the freezing-point of water the average speed of a molecule of hydrogen is about one mile a second, whereas that of a molecule of oxygen is only about $\frac{1}{4}$ mile a second. Individual molecules attain speeds much higher than the average, so that at the outer limits of the Earth's atmosphere molecules of hydrogen from time to time rebound outwards with speeds that are greater than the velocity of escape and never return. But a molecule of oxygen or nitrogen will very rarely attain a speed about 30 times greater than its average speed, which it must do before it can escape. Thus though the Earth has been able to retain an atmosphere, the hydrogen, which was probably the chief constituent of the atmosphere when the Earth was very young, has almost entirely been lost. The velocity of escape from the Moon, on the other hand, is so low that the hydrogen originally present in its atmosphere must have been lost very quickly, whilst the oxygen, nitrogen and other constituents, though escaping more slowly, have long since been completely lost,

with the result that now the Moon has no atmosphere at all.

We can convince ourselves in a very simple way that the Moon has no atmosphere. If, on any clear night, the position of the Moon relative to nearby bright stars be noted, it will be seen in the course of an hour or two that the Moon is changing its position relative to the stars. The Moon appears to move eastwards amongst the stars, and it is a consequence of this eastward motion that the Moon rises on an average 50 minutes later each night than the preceding night. This apparent motion is a consequence of the motion of the Moon in its orbit round the Earth. From time to time the Moon may be seen to pass in front of a star, or to "occult" it, as the astronomer terms it. When this happens, the star is seen to disappear instantaneously. When the Moon is near first quarter, the advancing eastern limb is dark and cannot be seen; if the star about to be occulted is viewed through a telescope, its disappearance at the moment of occultation is startling in its suddenness. If the Moon had any atmosphere, the rays of light from the star would be bent or refracted in passing through the Moon's atmosphere; the nearer the rays approached the edge of the Moon, the greater would this bending be, and instead of disappearing suddenly the star would gradually fade from view.

The Moon, having no atmosphere, must also be entirely devoid of water. If there were water on the Moon, evaporation would take place when the surface of the Moon was heated by the Sun and the molecules of water-vapour would gradually escape into

space. This process would continue until there was no water left. This conclusion is in agreement with what we observe on the Moon with the aid of a telescope. In a powerful telescope objects on the Moon the size of St. Paul's Cathedral can be distinguished. If there were seas, rivers, lakes or even large ponds, we should frequently see them shining brightly when they were suitably placed to reflect the sunlight in the direction towards the Earth. Nothing of this sort has ever been observed.

The Moon moves round the Earth under the influence of the Earth's gravitation, one complete revolution being made in rather less than one month. The average speed of its motion is not much greater than half a mile a second—but little more than that of a high-explosive shell. This is much less than the speed of about 20 miles a second with which the Earth moves in its orbit around the Sun. The Moon, like the Earth, is also rotating. One complete rotation on its axis takes exactly the same time as one revolution in its orbit round the Earth; in other words, the length of a day on the Moon, as measured from, say, noon to the next noon, is about one month. It is for this reason that we always see the same face of the Moon; the other side of the Moon is completely and for ever hidden from our sight.

The Moon does not shine by its own light but reflects some of the light from the Sun which falls upon it. The average reflecting power of the surface of the Moon is low, for only one part in fourteen of the sunlight falling on the Moon is reflected, the remainder being absorbed. It can be seen with the naked eye that some portions of the surface

appear brighter than others (Plate II). Different substances have different reflecting powers; chalk and white sand, for instance, reflect much more than dark-coloured rocks, such as granite or basalt. The brightest portions of the Moon have a reflecting power about equal to that of white sand, but the average for the whole surface corresponds to that of darkish rocks. It may therefore be concluded that the greater portion of the surface of the Moon is of a brownish colour.

At any time only one half of the surface of the Moon can be in sunlight, the other half being in darkness. The amount of sunlit surface which we can see depends upon the relative positions of the Earth, Moon and Sun. When it is Full Moon, the Sun, Earth and Moon are practically in a line, with the Earth between the Sun and the Moon; the whole of the bright surface of the Moon then faces the Earth. When it is New Moon, the three bodies are again in a line, but the Moon is then between the Sun and the Earth, with its dark side towards the Earth. At other times facing the Earth is a portion of the bright side of the Moon and a portion of the dark side. Thus we have the varying appearance of the phases of the Moon. Just after New Moon, when the Moon is seen as a narrow bright crescent, the remainder of the disc of the Moon may be dimly seen; this appearance is known as "the Old Moon in the arms of the New." The cause of this appearance will be readily understood if we remember that the Moon is then between the Sun and the Earth and nearly in a line with them. The dark face of the Moon is turned towards the Earth, but

PLATE III.—PORTION OF MOON, INCLUDING THE SEA OF SERENITY (THE UPPER DARK AREA), AND THE SEA OF TRANQUILLITY (THE LOWER DARK AREA).

Note the line of lava flow. The large crater at the right-hand edge is Posidonius, 62 miles in diameter.

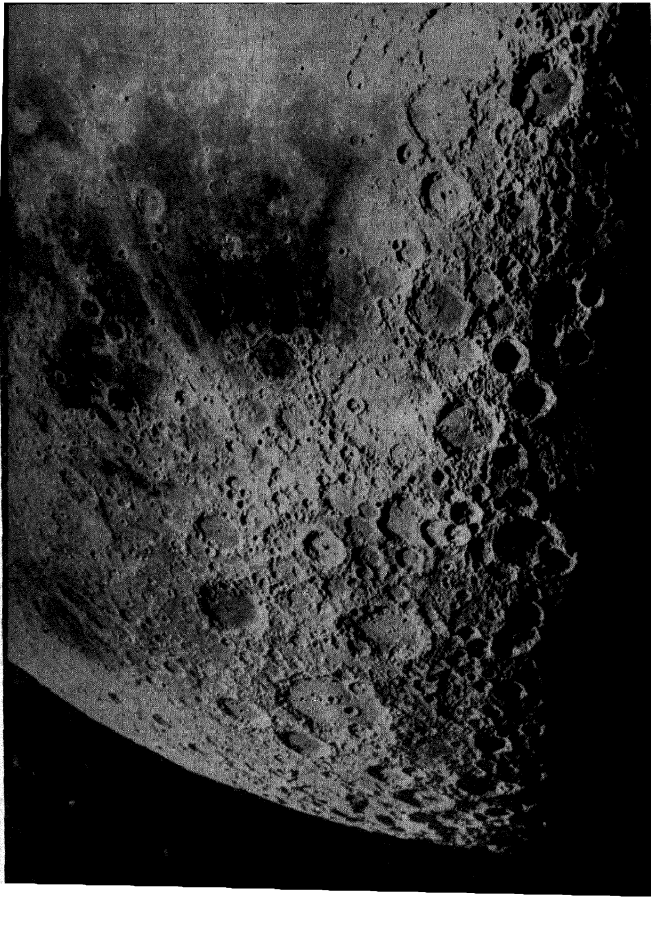


PLATE IV.—PORTION OF THE SOUTHERN HALF OF THE MOON, SHOWING NUMEROUS CRATERS, SOME WITH AND OTHERS WITHOUT CENTRAL PEAKS.

The dark area is called the Sea of Clouds.

the bright side of the Earth (that is, the side which faces the Sun) is towards the Moon. The Earth reflects some of the sunlight falling upon it back towards the Moon and the face of the Moon becomes dimly visible by means of this "Earth-light."

We have stated above that at the times when the Moon is new or full, the Sun, Earth and Moon are in a straight line. This is not strictly correct, for in general the Moon will be either above or below the plane of the orbit which the Earth describes round the Sun. When the three bodies are actually in line, we observe an eclipse. If this occurs at Full Moon, the Earth is between the Sun and the Moon, and cuts off the sunlight from the Moon, we then have an eclipse of the Moon, and this is visible over the whole hemisphere of the Earth facing the Moon. The Moon does not become invisible when totally eclipsed in this way but appears of a dull copper colour; this is due to rays of light from the Sun being refracted or bent in their passage through the atmosphere of the Earth so that some are thrown on to the Moon's surface.

If it is New Moon when the three bodies are in a line, the Moon is between the Sun and the Earth and we have an eclipse of the Sun. Though the Moon is very much smaller than the Sun, it is so much nearer that it is possible, but only just possible, for the Moon completely to obscure the Sun. When this happens we have a total eclipse of the Sun. If, at the time of eclipse, the Moon happens to be at its greatest distance from the Earth, it is unable completely to obscure the Sun. We then see, at the time of mid-eclipse, a narrow ring of sunlight all

round the Moon; this is called an annular eclipse. A total or an annular eclipse is visible only over a small portion of the surface of the Earth; over a much larger area, a partial eclipse, when a part only of the Sun is obscured, will be seen. We learn therefore that an eclipse of the Moon can only happen at Full Moon and an eclipse of the Sun can only happen at New Moon. It can be shown that there must be at least two eclipses (partial or total) in any year; if there are only two, they must both be eclipses of the Sun. There were only two eclipses in 1933; there will be only two in 1940. There cannot be more than seven eclipses in a year, of which there may be five of the Sun and two of the Moon (as in the year 1935) or four of the Sun and three of the Moon (as in 1917). Though eclipses of the Sun are more frequent than eclipses of the Moon, eclipses of the Moon are more commonly seen, because an eclipse of the Moon is visible from half of the surface of the Earth, but an eclipse of the Sun is visible from only a limited area.

If by means of our rocket we were able to land on the Moon, we should find a world very different from our Earth. There are no oceans or rivers or water of any sort, nor are there any trees or other vegetation. There are no signs of any habitation. Complete stillness reigns everywhere; no breezes blow, for there is no atmosphere. There is no dust or haze to impair the visibility. Not a sound is heard to disturb this unnatural stillness. The Sun and stars appear much bluer than they do to us on Earth, and the stars shine brightly in broad daylight in a sky of inky blackness. We should notice that

they shine steadily without a twinkle. The shadows cast by the Sun are black, with sharp and hard outlines. Large areas of the surface are flat desert expanses; but most of the surface is extremely mountainous. The mountain walls are for the most part sharp and jagged, for the weathering action of wind and rain and the eroding effect of streams and rivers have been absent. (Note the shadows of the mountains in Plate V.) During the long lunar day, equal to about 14 of our days, the Sun strikes down with pitiless fury; at noonday on the equator the rocks are heated to a temperature well above the boiling-point of water. But as soon as noon has passed the temperature begins to fall, for there is no water-vapour to act as a blanket in retaining the heat. Towards evening the fall is very rapid. By sunset the temperature is well below the freezing-point of water. Sunsets on the Moon are strangely different from those to which we are accustomed on the Earth. We should never see the Sun shining red through clouds or haze as it approaches the horizon, with the clouds reflecting its glory. Until the Sun finally disappeared beneath the horizon it would shine with the same steely blue light and then total darkness would fall with bewildering suddenness. Of twilight there would be none. Even in the daytime, in the mountain valleys sheltered from the Sun, it would be pitch-dark. During the long cold night the temperature falls far below anything experienced in the coldest regions of the Earth's surface, to about 150° F. below freezing-point. The temperature would be even lower were it not that the rocks had been heated to such a great

extent during the daytime. The Moon is certainly not a place to be recommended for a pleasure trip.

We have mentioned that the Moon is an extremely mountainous body. There are mountain ranges on the Moon which appear very similar to mountain ranges on the Earth. One of the ranges, called the Apennine Range, is shown in Plate V. But the mountain ranges are few in number. Most of the mountainous formations on the Moon are in the form of mountain rings of various sizes. The largest of these have diameters exceeding 100 miles and could contain within them two or three English counties. There are others of all sizes down to small ones which are only visible in very powerful telescopes. The majority of these *craters*, as they are called, are from 5 to 20 miles in diameter. There are at least 30,000 of them on the side of the Moon which faces us. The typical crater is practically circular; the mountain ring wall rises to a height of anything up to 20,000 feet above the surrounding country. Yet if we were to stand near the centre of one of the larger craters, no trace of this high encircling mountain wall would be visible. The mountain wall is usually much more precipitous on its inner slopes than on its outer slopes. The floor within the ring is sometimes above and sometimes below the level of the surrounding surface. At the centre of the crater there is often, but not invariably, a mountain peak or a group of peaks. In Plates III and IV may be seen examples of craters both with and without central peaks. On some portions of the surface the craters are extremely numerous. Such a portion is shown in Plate IV. It will be

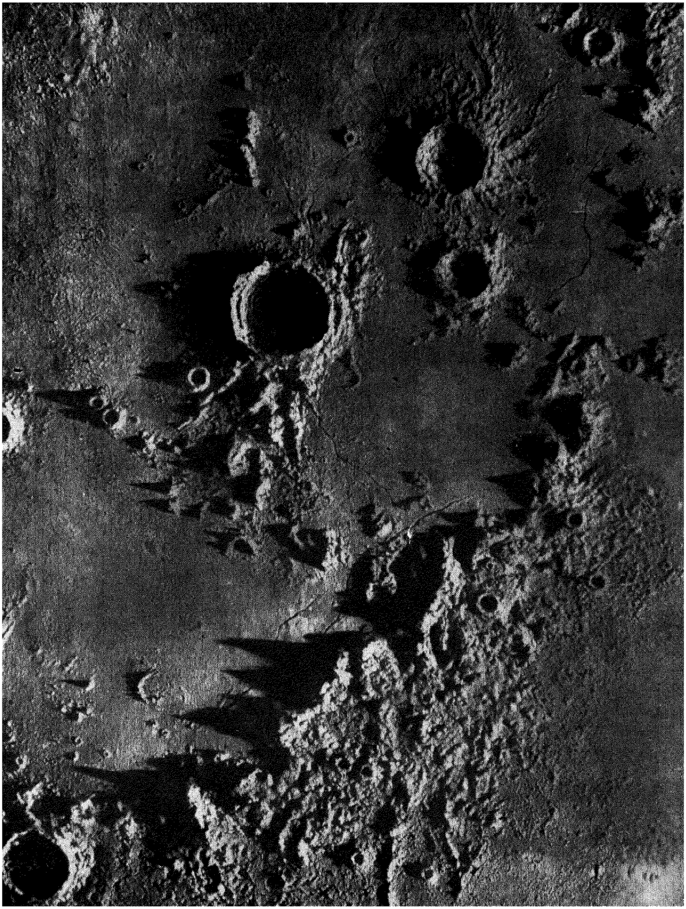


PLATE V.—THE RANGE OF LUNAR MOUNTAINS, CALLED THE APENNINES.

The range extends for about 450 miles and contains upwards of 3,000 peaks. The highest peak, Mount Huyghens, is 21,000 feet high. The large crater is called Archimedes. It has a diameter of 52 miles : the crater wall is at an average height of about 4,300 feet above the surrounding plateau. There is no central peak.

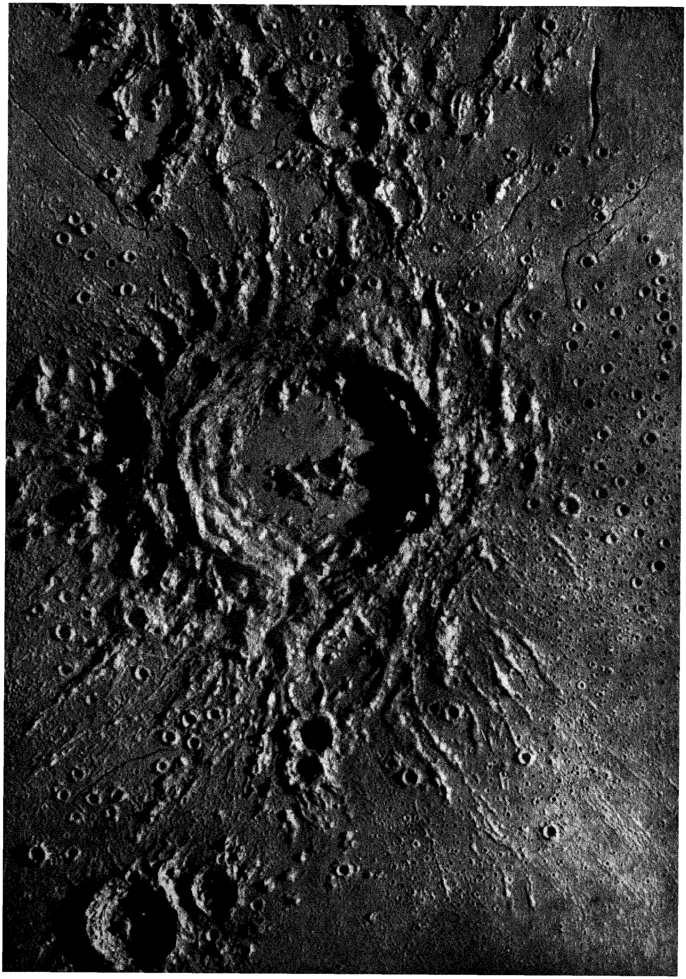


PLATE VI.—THE RING CRATER, COPERNICUS, IS ONE OF THE MOST IMPRESSIVE CRATERS ON THE MOON.

Its diameter is 46 miles. Within it is a group of craters, three of which are upwards of 2,400 feet high. The ring wall rises to 12,000 feet above the level of the plateau.

noticed that small craters are often to be found within larger ones and that occasionally a newer crater has encroached upon the ring wall of an older crater. A typical crater, Copernicus, is shown in Plate VI. Travel of any sort, other than by aeroplane, over such portions of the surface of the Moon would be extremely arduous and railway construction would tax the ingenuity of the most skilled engineers.

The term *crater* and the general appearance of these formations suggest a volcanic origin. The name is unfortunate because it is misleading, for we cannot be certain that the craters have been produced by volcanic action. It is difficult to believe that a crater of 1 mile in diameter and another crater exceeding 100 miles in diameter can both have been produced by volcanic action. As there are craters of all sizes between the smallest and the largest, we are compelled to believe that they have all had a common mode of formation. We might argue that as there are no volcanic formations on the Earth which at all resemble the craters on the Moon, the lunar craters cannot have been formed by volcanic action. This, however, is an argument which can be used against any suggested explanation of their formation. We must remember also that the effects of erosion and denudation from water, wind and blown sand have entirely changed the appearance of terrestrial formations, and we cannot assert that the Earth may not also when it was young have had crater formations like those on the Moon.

Another explanation which has been suggested supposes that soon after the Moon was born and a

solid crust had commenced to form, the generation of gas or steam beneath the crust caused it to blow out into vast bubbles at its weakest points. The bubbles expanded as the pressure increased and at last burst. The central portion of the bubble fell back into the liquid interior and became molten again, but all round the opening the circular rim was left, forming the mountain wall. The crust formed again inside the ring. The same process may have occurred many times over; once a bubble had burst, the newly formed crust within it would be relatively weak and a further bursting at the same point would be liable to occur.

The extensive dark areas on the Moon have from the time of Galileo been called *maria* or seas; when this name was given it was believed that they were actually expanses of water. The name has been retained, though it has long since been realised that they are not seas. Plate III shows the Mare Serenitatis and the Mare Tranquillitatis. It is possible that as the Moon cooled large areas of the crust subsided and were overrun by molten lava. Some of the seas show irregular wave-like markings which appear to mark the limits of successive outflows of lava. Such a marking across the Sea of Serenity is to be seen in Plate III.

Other interesting features can be seen on the Moon's surface. There are many deep, narrow valleys which are called rills. More interesting are the clefts which run for hundreds of miles across mountains, valleys and plains. They are perfectly straight and about half a mile in width, and are evidently vast crevasses of unknown depth produced

by the cracking of the Moon's surface. They would offer serious obstacles to any lunar explorer.

Most interesting and puzzling, perhaps, of all the lunar formations are the bright streaks which radiate from some of the larger craters. The system of rays from the large crater Tycho is shown in Plate II. These streaks, which in a photograph give the Moon somewhat the appearance of a peeled orange, are best seen at the time of full Moon; from 5 to 10 miles in breadth, they may stretch for many hundreds of miles, crossing mountains, valleys and other craters without any change in width or colour. They cast no shadows and cannot therefore be much elevated above the surface. They have the appearance of deposits of fine volcanic ash, but why such deposits should occur in the form of straight streaks and not be uniformly spread around the parent crater is a mystery. Another suggestion is that they mark the tracks of fine rifts which are too narrow to be visible and that the surface has been stained by vapours which have arisen from these rifts.

It will be evident that the various problems of lunar topography present a fertile subject for speculation, but, since geological evidence for or against any theory cannot be obtained, we can do no more than form our own conclusions as to the probability or improbability of the various theories which have been put forward.

The Moon is of great economic importance to mankind because it is largely responsible for the ocean tides. The tides are due to a regular rise and fall of the water, generally twice a day. This rise and fall is due to the gravitational attraction of the

Moon and the Sun. The Moon attracts the ocean directly beneath it more powerfully than it attracts the solid Earth and tends to pull the two apart, with the result that the water becomes heaped up beneath the Moon. On the far side, the Moon attracts the ocean less powerfully than the solid Earth and again tends to pull the two apart, causing another heaping up of the water. As the Earth rotates, the oceans move over its surface, the heaping up of the waters tending to occur at the point beneath the Moon and at the point diametrically opposite. The movement of the oceans is impeded by various causes and is affected by the local land configurations, so that the actual phenomena are more complicated. The Sun also exerts a tide-raising force, but the effect of its greater distance more than counterbalances the effect of its greater mass, with the result that the tide-raising force of the Sun is less than half that of the Moon. Bearing these facts in mind, some of the main phenomena shown by the tides can be simply explained. At any given place, the height of the tide varies considerably ; the rise and fall of the tide is greatest at *spring tides* and lowest at *neap tides.* The spring tides occur when the tide-raising forces of the Sun and Moon are acting together ; this happens when the Sun, Moon and Earth are in a line, in other words, at New Moon or Full Moon. When the Sun and Moon are in opposing positions, i.e. near first and last quarters of the Moon, we have neap tides. The retardation from day to day in the times of high and low tides is well known; this is a consequence of the retardation from one day to the next in the time of rising of the Moon, since the heaped-up waters

follow the motion of the Moon. Spring tides at the same place are not always of the same height; a variation is caused by the change in the distance of the Moon from the Earth, in consequence of the Moon's orbit being not circular but elliptical. The tidal effect due to the Moon is at its greatest when the Moon is at its nearest to the Earth, the range in the tides due to the change in distance of the Moon being about 30 per cent. The greatest rise and fall of the tide happens when New or Full Moon occurs at the time when the Moon is at its nearest to the Earth.

Chapter III

THE SUN'S FAMILY OF PLANETS

From night to night we can detect no change in the relative positions of the so-called " fixed stars "; even the span of a human lifetime would not be sufficient for any changes to be apparent to the naked eye, though refined observations with telescopic aid reveal that the positions are slowly changing. It was known to the ancients that there were a few bodies which moved about amongst the stars, and these they termed planets or wanderers (Latin, *planeta*, a wanderer). Under this term they included the Moon, Mercury, Venus, the Sun, Mars, Jupiter and Saturn; these bodies were supposed to move around the Earth and to be in this order of increasing distance from the Earth. The term " planet " is now restricted to the bodies which are revolving around the Sun in definite orbits. It includes the Earth ; the five bodies which have been known from prehistoric times, viz. Mercury, Venus, Mars, Jupiter and Saturn ; the three bodies which have been discovered in comparatively recent times, viz. Uranus, Neptune and Pluto ; and many hundreds of small bodies which are termed minor planets or asteroids. These bodies form the Sun's family of planets.

Certain regularities in the arrangement of this family may be noticed. The planets all move around the Sun in the same direction and their

paths lie very nearly in the same plane. It is therefore only in certain regions of the sky that the planets are to be found; they are never very far distant from the "ecliptic," the path amongst the stars which the Sun appears to describe in the course of a year as a result of the motion of the Earth around the Sun. This path is marked in any good star atlas. The planets also rotate about their axes in the same direction as that in which the planets themselves revolve around the Sun.

Similar regularities are also seen in the satellite systems of the planets, with one or two trivial exceptions. The Earth has one satellite, the Moon, which revolves around the Earth just as the Earth revolves around the Sun. Jupiter and Saturn have nine satellites each, Uranus has four, Mars has two and Neptune has one. In general, the rotations of these satellites about their axes and their revolutions about the parent bodies are in the same direction as that in which the planets themselves move around the Sun. There is a definite "rule of the road" to which the members of the Sun's family conform. These regularities cannot be the result of mere chance and undoubtedly point to some common origin for all the members of the Sun's family. What this origin is we shall consider in Chapter XIII.

It is desirable to have a general idea of the scale and arrangement of the solar system. If we represent the diameter of the Earth by 1 inch, the Sun must be placed at a distance of 320 yards and will be 9 feet in diameter; the Moon will be only $2\frac{1}{2}$ feet away and will be $\frac{1}{4}$ inch in diameter, or about the size of a pea. Jupiter, the largest of the planets,

will then be about the size of a football, with a diameter of 11 inches. Mercury is somewhat larger than the Moon, being about $\frac{2}{5}$ inch in diameter and about equal in size to the largest of the satellites of Jupiter. The minor planets would hardly show on this scale; the largest of them would be about the size of the letter "o" in this type, the

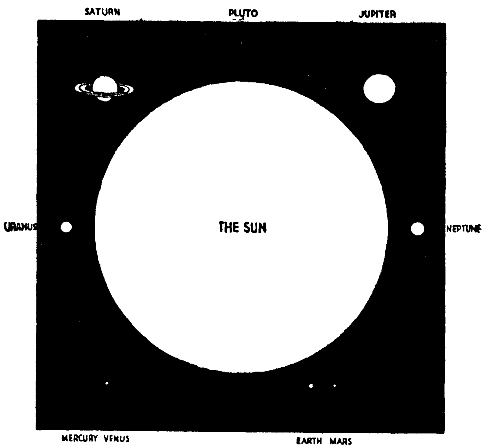


FIG. 1.—Relative sizes of Sun and planets.

smallest would be much smaller than the full-stop. Saturn is large, but smaller than Jupiter. The next largest are Uranus and Neptune, which are about the size of a grape-fruit. Pluto is probably smaller than Mercury. Jupiter would be at a distance of nearly 1 mile, whilst Pluto would be more than 7 miles away. The sizes of the planets relative to each other and to the Sun are illustrated in Fig. 1.

The movements of the planets in their orbits take

place in accordance with certain rules which were formulated by Kepler between the years 1607 and 1620. The three famous laws of Kepler may be stated as follows:

1. Each planet moves round the Sun in an ellipse and the Sun occupies one of the foci of the ellipse. An ellipse can be simply drawn by placing two pins in a piece of paper, running a loop of cotton around them, drawing the loop tight with the point of a pencil and moving the pencil round. The positions of the two pins are called the foci of the ellipse. If the two foci are far apart, the ellipse is very elongated in shape; if they are brought nearer and nearer together, the ellipse becomes more and more nearly similar to a circle, and, in the limiting case when the two foci coincide, the ellipse becomes a circle. None of the orbits of the planets, except those of Mercury, Pluto and some of the asteroids, differs very greatly from a circle.

2. Each planet moves in its orbit round the Sun in such a way that the line joining it to the Sun moves through equal areas in equal times. It follows that the motion of the planet in its orbit is most rapid when the planet is at its nearest to the Sun and slowest when it is at its greatest distance.

3. The time in which a planet travels once round its orbit is related to the size of the orbit. The actual relationship is that the squares of the times of orbital revolution are proportional to the cubes of the distances of the planets from the Sun. It may be deduced that the actual velocity of the planet in its orbit is inversely proportional to the square root of its distance from the Sun. Thus if

there were a planet whose distance from the Sun were four times that of the Earth, its speed in its orbit would be only one-half that of the Earth. The further the planet from the Sun, the slower the speed with which it moves. This is in direct contrast to what happens when a rigid body rotates. If we think, for instance, of a wheel spinning round, the speed of a point on the rim is greater than the speed of a point on the hub; the speed of any point on a spoke is directly proportional to its distance from the centre of the hub. If the solar system were rotating like a rigid body, the most distant planets would move the fastest.

Newton showed that these empirical laws of Kepler could be simply explained by the universal law of gravitation. It is the gravitational pull of the Sun which prevents the planets flying away into space and keeps them moving in their paths around the Sun. The nearer the planet is to the Sun, the greater is the pull of the Sun and the faster the planet must move to prevent itself falling towards the Sun. Thus we find that Mercury is hurrying around with a speed of about 32 miles a second, completing one revolution of its orbit in 88 days, whereas Pluto, which is so far away that it takes about 248 years to go once round its orbit, is a comparative laggard, with a speed of little more than 3 miles a second, a speed which—though high when judged by ordinary terrestrial standards—is low when compared with those of most other celestial bodies.

The planets, like the Moon, are not self-luminous, but shine by the light from the Sun which they

reflect or scatter back into space. Unless a planet has a store of heat in its interior—as it would have, for instance, if it were largely composed of radioactive materials—there must be a general balance between the amount of energy which it receives in the form of light and heat from the Sun and the amount which it sends back into space. The amount of solar energy falling on any planet can be computed without difficulty, for the size of each planet and its distance from the Sun is known. The energy emitted by the planet can be detected and measured with the aid of a sufficiently powerful telescope and a sensitive energy-detecting device such as a thermopile or a bolometer. By placing a small transparent cell containing water in front of the thermopile, the radiation of long wave-length is absorbed and only the short wave-length radiation falls on the thermopile; thus the radiations of long and short wave-lengths can be separately measured and it becomes possible to deduce the temperature of the planet. The temperatures obtained in this way are in close agreement with those deduced from the amount of solar energy falling on the planet, and it can be inferred that none of the planets has any appreciable source of internal heat. These temperatures are not necessarily the temperatures of the actual surface of the planet, for if the planet has a covering of cloud the cloud layer may play an important part in modifying the surface temperature, as we have already seen in the case of the Earth.

Mercury, the planet nearest to the Sun, is the smallest of the planets with the possible exception of Pluto, the asteroids being left out of consideration.

Its distance from the Sun is about 36 million miles. It is too near to the Sun to be seen with the naked eye, except in the evening shortly after sunset, or in the morning shortly before sunrise; it is more favourably placed for observation in the tropics than in more northerly or southerly latitudes.

The diameter of Mercury is about 3,000 miles, or about half as large again as the diameter of the Moon. The Earth could contain about sixteen bodies of the size of Mercury. Its weight is not known with great accuracy, but it is probably only about one-twenty-fifth of the weight of the Earth. The velocity of escape from Mercury is not much greater than the velocity of escape from the Moon, and we may conclude with reasonable certainty that Mercury has no atmosphere. Direct confirmation of this conclusion can be obtained, for we find that Mercury reflects only about 7 per cent. of the sunlight which falls upon it; the remainder is absorbed by the surface rocks and emitted again as heat radiation of long wave-length. The Moon reflects the same proportion. If the surface were cloud-covered the proportion would be much higher.

The absence of any atmosphere on Mercury necessarily implies also the complete absence of water. Any water there may once have been will gradually have been evaporated, and the water-vapour, like the atmosphere, slowly dissipated away into space. It may be concluded that Mercury is a dead, arid world.

We cannot find out much about its surface, for there are no well-defined markings to be seen on it,

as there are on the Moon. Careful observation has shown little more than faint ill-defined shadings, visible only under favourable conditions. The study of these markings has shown that the planet always turns the same face to the Sun, just as the Moon does to the Earth. Thus the day and the year on Mercury are of the same length, and each equal to 88 of our days. By the word "day" we here mean the period of rotation of the planet about its axis. If, however, we use the terms day and night to express the periods of light and darkness, we can say that there is perpetual day over one half of Mercury and perpetual night over the other half.

The temperature on the sunlit face of Mercury is extremely high; by direct measurement it is found that the temperature of the portion of the surface which has the Sun overhead is about equal to that of molten zinc. The opposite side of the planet must be intensely cold. Near the border line between the two regions it would be possible to pass in a comparatively short journey from a region of intense cold, with a temperature lower than any temperatures experienced on our Earth, to a region of intense heat far surpassing that of our tropical regions. The faint markings are occasionally obscured in certain parts of the planet, as though by clouds of dust. It is possible that there are active volcanoes on Mercury, which from time to time are in violent eruption and eject clouds of fine dust to a considerable height above the surface. The dust gradually falls to the ground but temporarily obscures the surface of the planet beneath it.

There are no winds to disperse the dust, because there is no atmosphere.

The next planet in order of distance from the Sun is Venus, which has special interest for us as being the planet which most nearly resembles the Earth. Venus may be regarded as the Earth's twin sister, for in size, in weight, in density and in general constitution it is not greatly different from the Earth. It is a little smaller, a little less massive and a little less dense. Its greatest angular distance from the Sun is about 46°, and so it can best be seen within a few hours after sunset or before sunrise. Its distance from the Earth varies widely, from 26 million miles to 160 million miles, and its apparent brightness varies considerably in consequence. Venus, like Mercury, shows phases in the telescope. Doughty, in his *Arabia Deserta*, states that the Arabs, who were possessed of great acuity of vision, called Venus the "horned star," and he considered that they were able to see it as a crescent with the naked eye. I do not think that there is any conclusive evidence of Venus actually having been seen as a crescent with the naked eye by a trustworthy observer who was entirely free from bias or prior knowledge.

It is when Venus is at her nearest to the Earth that she appears as a thin crescent. As the distance increases, more of the bright disc becomes visible; the increasing distance tends to make the planet appear less bright, but the change in phase acts in a contrary direction; the resultant of the two effects is that the brightness continues to increase for about 36 days from the time when Venus is at her

nearest. Thereafter the effect of the increasing phase is more than counterbalanced by the greater distance. When at her brightest, Venus is much brighter than any star or any other planet and can be seen without difficulty by the naked eye in broad daylight. I have on more than one occasion seen it without looking for it, and without realising at first that I was actually looking at Venus.

The velocity of escape from Venus is slightly lower than the velocity of escape from the Earth. It is therefore to be anticipated that Venus has succeeded in retaining an atmosphere. This anticipation is fully confirmed by observation. Venus reflects about 60 per cent. of the sunlight which falls upon it. This is about equal to the reflecting power of freshly fallen snow and is higher than the reflecting power of any other planet. No known rocks or soils have so high a reflecting power, and it may be inferred that Venus is covered with a highly reflecting layer of cloud. The appearance of the planet in the telescope is consistent with this inference. No surface markings can be seen, though ill-defined darkish shadings have been seen at times. These do not persist for long and are undoubtedly atmospheric objects of some sort.

Photographic plates which are sensitive to the infra-red rays, whose wave-length is outside the limit to which the human eye is sensitive, have been used recently with much success for the photography of distant landscapes. Such photographs show far more detail than those taken on ordinary plates. (See Plate VII.) The reason is that the infra-red rays are of long wave-length and are therefore able

to pass through a greater length of atmosphere than the actinic rays of short wave-length, which are rapidly scattered in all directions. Photographs of Venus have been obtained using plates specially sensitive to infra-red light, in the hope that these rays would penetrate through the atmosphere of Venus and tell us something about the surface of the planet. But they show no surface details; even the infra-red rays cannot penetrate the planet's atmosphere. This is not surprising, if the planet has a permanent dense covering of cloud.

We can attempt to gain some information in another way. The light reaching us from Venus can be compared with the light which we receive directly from the Sun. In neither case is the light pure sunlight. The light which we receive from the Sun directly has some wave-lengths weakened or missing because of absorption in the atmosphere of the Earth. Oxygen cuts out one set of wave-lengths, water-vapour another set and so on. If we find that light of a certain wave-length is missing from sunlight, it may be either because this light has been absorbed by the outer layers of the Sun or because it has been absorbed by the atmosphere of the Earth. We can easily distinguish between these two possibilities by comparing the light received from the Sun when it is high in the sky with that received near sunset. As the Sun gets lower in the sky, its rays have to pass through a greater extent of the Earth's atmosphere in order to reach us, and any effects produced by absorption by our atmosphere become intensified. In a similar way, if we compare the light coming to us directly from

the Sun with that which has penetrated to the cloud layer of Venus, then out again and so through our atmosphere to us, the differences must be due to the absorption in the outer layers of the atmosphere of Venus. The information which we may hope to obtain in this way is necessarily limited, for a group of elements which includes hydrogen, helium, nitrogen, argon and neon does not absorb any of the sunlight, and so we cannot detect these elements, even though they may be present.

But once again Venus defeats our attempts to wrest her secrets from her. No traces either of oxygen or of water-vapour are to be found; the test for oxygen is much more sensitive than that for water-vapour, and we can only draw the negative conclusion that the amount of oxygen above the cloud layer which covers the planet is less than the one-thousandth part of the quantity in the atmosphere of the Earth. The only positive information that we have derived is a clear indication of the presence of carbon dioxide in the atmosphere. The amount of carbon dioxide above the cloud layer is surprisingly large; it is equivalent to a layer 2 miles thick at the Earth's surface. The total amount above the surface of Venus must be considerably greater. There is very little carbon dioxide in the Earth's atmosphere. The whole atmosphere of the Earth is equivalent to a layer 5 miles thick at the surface; of this total, the carbon dioxide amounts to a thickness of only 30 feet, so that there is several thousand times more carbon dioxide in the atmosphere of Venus than in our atmosphere.

Little more is known about the length of the day

on Venus. It is reasonably certain that it cannot be less than 2 or 3 of our weeks and equally certain that the planet does not always turn the same face to the Sun; if this were the case the dark side would be very cold, whereas it has been found that a considerable amount of heat is radiated from the dark side of the planet. The day on Venus must therefore be considerably less than 224 of our days. A day equal to 2 or 3 of our weeks seems probable. As the year on Venus is equal to about 32 of our weeks, there are only some 10 or 15 days in the year.

In the face of all this negative evidence, any attempt to describe the conditions existing on Venus must be very speculative. Since the planet is nearer than our Earth to the Sun, we may expect the surface of Venus to be much warmer than that of the Earth. Direct measurement of the temperature shows that it is practically uniform over the planet; the temperature of both day and night sides is about 15° F. below zero, but, as in the case of the Earth, the high clouds are likely to be much cooler than the surface. The failure to detect water-vapour, even though the tests are not fully decisive, is perhaps not surprising. It is difficult to conceive of what the cloud layer over Venus is composed, if it is not condensed water-vapour; the region above the clouds is probably too cold for water-vapour to exist without condensing. The water-vapour in the Earth's atmosphere is almost entirely confined to the lower layers; clouds at a height greater than about 5 miles are rarely found, unless perhaps in tropical regions. It seems probable that there are oceans on Venus; the high temperature at the surface

would then result in extensive evaporation and the formation of a dense cloud layer. We may conclude that Venus must have a hot, damp climate with heavy precipitation.

The failure to detect any traces of oxygen is the most surprising feature about Venus, for in other respects conditions are not greatly unlike those on the Earth. This may possibly point to a lack of vegetation on the planet. Oxygen is chemically an active substance, which unites readily with other substances to form compounds. On our Earth vegetation plays a great part in replenishing the store of oxygen; if Venus has no vegetation, then the absence of oxygen is perhaps explicable.

The last to be considered of the four inner planets is Mars, whose average distance from the Sun is about half as large again as the distance of the Earth from the Sun. When at its closest to the Earth, it is only about 35 million miles away and appears brighter than any other planet except Venus. Mars is considerably smaller than the Earth—its diameter being little more than half that of the Earth—and its weight is only about one-tenth of that of the Earth. As the velocity of escape from Mars is rather less than one-half of the velocity of escape from the Earth, it is not to be expected that Mars will have an extensive atmosphere; we may indeed anticipate that the atmosphere has largely been lost. The appearance of Mars in the telescope confirms this; it is a beautiful object with a strong orange colour, on which dark and light surface markings may be clearly seen. Around whichever pole is visible there is a bright white cap, called the polar

cap. The two polar caps show regular seasonal changes in size; the northern cap, for instance, shrinks during the northern summer, whilst the southern cap grows. During the northern winter the northern cap grows and the southern cap shrinks. At midwinter either cap has a diameter of somewhere about 3,000 miles and extends about half-way from the pole to the equator. The southern cap sometimes disappears altogether in the summer, but the northern cap never shrinks to a diameter less than about 200 miles. In contrast to the polar caps, the reddish areas on the planet show little or no change with the seasons, and in them we probably see the actual surface of the planet. The amount of light reflected by the surface of the planet is what would be expected from moderately dark rocks, and we may conclude that Mars has a rough rocky surface.

There are other markings on Mars which are of a bluish-grey or greenish shade; they are found mainly in the southern hemisphere. The early observers of Mars thought that these were oceans and named them accordingly. It is certain that there are no large sheets of water on Mars, for, if there were, brilliant reflections would be seen from them when the Sun is suitably placed; but such reflections have never been observed. These markings, though fairly permanent in form and position, show changes of a seasonal nature and are sometimes much less conspicuous than at others; changes in colour have also been noticed. They may be in part an atmospheric phenomenon and possibly in part the effect of local precipitation of rain.

In addition to these broad general features, which may be seen with a telescope of moderate size, some observers have claimed to see a number of narrow, dark, straight markings on Mars, extending in some cases for thousands of miles. The existence of such markings was announced by Schiaparelli in 1877, and they were interpreted by him as a network of channels for water. He designated them by the Italian word *canali*. Other competent observers also claim to have seen these canals; in particular Lowell and Slipher, observing in the clear air and at the high altitude of the Flagstaff Observatory in Arizona, have studied them. One of Lowell's drawings, showing many canals, is reproduced in Plate VII. Other skilled and equally competent observers have failed to detect them. The canals have never been shown on a photograph of the planet; but it has to be remembered that with the largest telescope the actual image of Mars is less than one-tenth of an inch in diameter. In order to photograph Mars, a larger image is necessary and so an enlarging lens is used; but in magnifying the image, the brightness is reduced and the time of exposure must be lengthened. Under the best conditions an exposure of several seconds is necessary to secure a photograph. Atmospheric tremors, even under the best conditions at the most favourably placed observatory, are sufficient to wash out such extremely fine detail.

It seems probable that though there is undoubtedly much fine detail on the surface of Mars, the canals, as described by Schiaparelli, do not actually exist and that their appearance is due to a subjective phenomenon: the eye tends to connect up faint irregular

markings, which are visible only with difficulty, by straight lines. The experiment was made of getting a class of schoolboys to copy a drawing of Mars on which there were no canals marked. Most of the boys at the back of the classroom put numerous straight lines into their drawing. There was no question here of any preconceived bias, for the boys were not aware that the drawing they were copying was a drawing of Mars.

When photographs of Mars are obtained, using first ultra-violet light and then infra-red light, some interesting differences appear. The infra-red photographs show the surface markings clearly; the ultra-violet photographs do not show them at all (Plates VII and VIII). This provides direct proof of the existence of an atmosphere on Mars. Sunlight of long wave-length is able to get through the atmosphere to the surface of Mars and out again; but the light of short wave-length is completely scattered before it can reach the surface. There is also evidence of clouds of two distinct types. Clouds of the first type are seen as whitish areas on the ultra-violet photographs, but do not show on the infra-red photographs; an example of a cloud of this type is to be seen in Plate VIII. Such clouds (which are not necessarily in any way similar to clouds in our own atmosphere) must be high up in the atmosphere of Mars, or they would not be seen in the ultra-violet photographs, and they must be sufficiently tenuous to allow the infra-red light to go through. Clouds of the second type show just the opposite effect; they are seen on the infra-red but not on the ultra-violet photographs. These clouds

appear yellowish to the eye. They must be much lower in the Martian atmosphere, because the ultra-violet light does not penetrate to them, though observations at the Flagstaff Observatory show that they may be as high as 15,000 feet above the surface. It is possible that they may be clouds of water-vapour, seen through a yellowish atmosphere.

The two polar caps show an unexpected difference in photographs taken with light of long and short wave-length. The most natural explanation of these caps is that they are surface deposits of snow or rime in the polar regions of Mars, analogous to the snow- and ice-caps of the polar regions of the Earth. If so, we should expect them to be most clearly shown on the photographs taken with the infra-red rays. Exactly the opposite is found; the caps are seen most clearly on the photographs taken with the ultra-violet rays and become less prominent the longer the wave-length of the light in which the planet is photographed. This is well illustrated by the two photographs of Mars in Plate VII. The polar caps must therefore be largely, though not entirely, an atmospheric phenomenon. It is possible that over the polar regions there are clouds of particles of snow or ice of no very great thickness, so that light of long wave-length can get through them, and that there is in addition a surface deposit of snow or ice. This surface deposit cannot be more than a few inches in thickness, or we should not observe such rapid melting of the caps as is seen during the summer months.

The image of Mars on a photograph in ultra-violet light is considerably larger than the image on

a photograph in infra-red light taken with the same telescope. The latter image, on which the surface details are clearly shown, must correspond to the solid globe of the planet; the ultra-violet image represents the atmospheric shell which surrounds Mars. The difference in the radii of the two images is from 50 to 60 miles, so that the atmosphere, though very thin, has a considerable depth. The total atmospheric pressure on Mars is probably not more than a few per cent. of that at the surface of the Earth. Plate VIII shows photographs of Mars obtained with ultra-violet and infra-red light; beneath them are the same photographs with their opposite halves in juxtaposition. The difference in size is at once apparent.

Until recently it was believed that the presence of both oxygen and water-vapour in the atmosphere of Mars had been definitely established, but the amount of each of these constituents was surprisingly small. Recent more delicate observations made at the Mount Wilson Observatory have failed to detect either oxygen or water-vapour, though an amount of oxygen equal to a thousandth part of that above an equal area of the Earth could have been detected with certainty. The tests for water-vapour are less sensitive, but it is certain that the total amount must be small. Yet there seems little reason to doubt that there must be both oxygen and water-vapour in the Martian atmosphere. The melting of the polar caps must produce water-vapour. The reddish colour of the surface of Mars is probably due to the oxidation of iron-bearing ores by atmospheric oxygen. It is possible that most of the oxygen on

Mars has been converted by the ultra-violet light of the Sun into ozone; the presence of ozone at the surface of Mars would greatly accelerate the oxidation of the rocks. The amount of ozone in the Earth's atmosphere is extremely small, its equivalent thickness being not more than one-eighth of an inch. Yet this thin layer completely prevents any of the extreme ultra-violet light from the Sun reaching the surface of the Earth; the completeness of this absorption makes it impossible to detect the presence of ozone in the atmosphere of Mars.

Observations of the temperature at the surface of Mars confirm the low amount of water-vapour in the atmosphere. Water-vapour absorbs strongly radiations of long wave-length and is therefore very effective in preventing the escape of the heat radiation from the surface of a planet. It is common experience that in damp tropical climates there is very little fall of temperature at night, whereas at places where the air is very dry the temperature falls rapidly after sunset. The maximum temperature on the Earth is usually reached during the afternoon and not at noon, when the Sun is highest in the sky and the solar radiation received is at its maximum. This is a consequence of the blanketing action of the water-vapour in our atmosphere preventing the rapid escape of the radiation from the heated surface of the Earth. But on Mars the maximum temperature occurs at Martian noon. This is proof that there is not sufficient water-vapour in its atmosphere to exert any appreciable blanketing effect.

Mars is naturally cooler than the Earth, being at a greater distance from the Sun. In the equatorial

regions the temperature may be as high as 50° F. during the daytime. The temperature falls very rapidly after noon, and even at the equator must be well below freezing-point by sunset. It is very low at night, probably reaching 130° F. below zero in the equatorial regions. The enormous daily range in temperature, of about 180° F. (equal to the difference between the boiling-point of water and the freezing-point), must make conditions extremely uncomfortable for any life that may exist on Mars. The temperature of the polar cap is somewhere about 100° F. below zero, but in the late summer, after the cap has disappeared, there seems to be little, if any, difference in temperature between the pole and the equator.

The length of the day on Mars does not differ very much from the length of our own day, being about 40 minutes longer. None of the other planets has a day which is so nearly equal to our own day.

The seasonal changes on Mars are much more pronounced in the southern hemisphere than in the northern. This is because the orbit of Mars round the Sun is much more elliptic than the orbit of the Earth. Whereas the distance of the Earth from the Sun does not vary by as much as 3 million miles, the distance of Mars from the Sun varies by 26 million miles. Mars is nearest to the Sun at the time when it is winter in the northern hemisphere and summer in the southern hemisphere; it is at its farthest when it is summer in the northern hemisphere and winter in the southern. The southern hemisphere, therefore, has a warmer summer but a colder winter than the northern.

Mars is the first planet to be met, as we travel outwards from the Sun, with more than one moon. It has two moons or satellites, but they are insignificant little bodies compared with our own Moon. The one which is nearer to Mars, called Phobos, is less than 40 miles across; the outer one, called Deimos, is even smaller, being only about 8 miles across. They are, however, so much nearer to Mars than the Moon is to the Earth that to a Martian observer Phobos would appear about the same size as the Moon appears to us. Phobos is only 5,800 miles and Deimos about 14,600 miles from the centre of Mars. Being so near to Mars, they move round it very rapidly, Phobos in about 7½ hours and Deimos in about 30 hours. The rapid revolutions of the two moons round Mars have some very curious consequences: thus, though both satellites move round Mars in the same direction as that in which Mars moves round the Sun, Phobos would be seen by an observer on Mars to rise in the west and to set in the east about 4¼ hours later. Deimos, on the other hand, rises in the east and sets in the west 66 hours later; between rising and setting Deimos would be seen to go through all its phases (new to full and back to new again) twice.

It is of interest to recall a remarkable prediction made by Dean Swift in *Gulliver's Travels*, published in 1726, a century and a half before the satellites of Mars were discovered. He relates that the astronomers of Laputa " have discovered two lesser stars, or satellites, which revolve about Mars, whereof the innermost is distant from the centre of the primary planet exactly three of his diameters, and the outer-

most five; the former revolves in the space of ten hours and the latter in twenty-one and a half." Considering the nearness to Mars of its satellites and their rapid revolution round it, the prediction was extraordinarily near the truth.

A curious empirical relationship between the distances of the planets from the Sun was formulated by Bode in 1772 and is known as Bode's Law. The law is as follows: to the numbers 0, 3, 6, 12, 24, 48, etc., add the number 4. The resulting numbers divided by 10 express, approximately, the distances of the planets from the Sun, in terms of the distance of the Earth as unity. The numbers obtained in this way are given in the first column of the following table. The second column gives the actual mean distances of the planets whose names are contained in the third column.

Bode's Law.	True Distance.	Planet.
0·4	0·39	Mercury
0·7	0·72	Venus
1·0	1·00	Earth
1·6	1·52	Mars
2·8	—	(Minor Planets)
5·2	5·20	Jupiter
10·0	9·54	Saturn
19·6	19·18	Uranus
38·8	30·07	Neptune
77·2	39·50	Pluto

At the time Bode formulated this law, Mercury, Venus, the Earth, Mars, Jupiter and Saturn were the only planets known. The distances of these planets agree closely with the distances given by the law, provided that a gap is left at the distance 2·8. In 1781 Uranus was discovered by William Herschel,

and it will be noted that the distance of Uranus is in good agreement with the value to be expected from Bode's Law. The more recently discovered planets, Neptune and Pluto, show an increasing deviation from the values required by Bode's Law. The gap at the distance of 2·8 times the Earth's distance can be regarded as filled by the discovery of a zone of small planetary bodies lying between Mars and Jupiter. The first of these bodies to be discovered, known as Ceres, was found accidentally by the Sicilian astronomer Piazzi. On January 1, 1801, in the course of observations for his star-catalogue, he observed a seventh-magnitude star where there had been no star a few days previously. The next night he found it had perceptibly moved with respect to the adjacent stars, and further observations showed that it continued to move. He named the new planet Ceres, after the tutelary divinity of the island of Sicily. In 1802, a second planet, Pallas, was discovered; a third, Juno, was found in 1804, and Vesta, the brightest of all the minor planets and the only one ever visible to the naked eye, was discovered in 1807. The fifth asteroid, Astræa, was not discovered until 1845, but since that date the list has grown rapidly. More than 1,200 have been observed sufficiently well for their orbits to have been computed; several hundred others have been discovered and lost again. They are for the most part very faint objects, usually discovered photographically. During the exposure, which may be several minutes or hours, the telescope is slowly moved by clockwork so that the effect of the rotation of the Earth is counteracted, and it continues

to point to the same stars as they move across the sky. The image of a star on the photographic plate is perfectly round, but the image of a minor planet is drawn out by its motion relative to the stars into a streak. The asteroids are easily detected in this way. Plate XI (*a*) shows a number of round images of stars together with three trails of asteroids.

Compared with the planets, the asteroids are all small bodies, whence the description of them as "minor planets." The largest of them, Ceres, has a diameter of about 480 miles; the diameter of Pallas is 306 miles, of Vesta 241 miles and of Juno 121 miles. Most of them, however, are not more than a few miles in diameter. It is quite certain that they are all devoid of any atmosphere; the velocity of escape from Ceres is, for instance, only about $\frac{1}{3}$ mile per second.

The asteroid zone extends from Mars to Jupiter, though in 1932 a tiny asteroid was discovered with a very elliptical orbit which actually passes within the orbit of Venus. This small body can approach to within about 3 million miles of the Earth and therefore comes nearer to us than any other known asteroid. In May 1932 it was only $6\frac{1}{2}$ million miles from the Earth. No closer approach of any planetary body has ever been observed.

The total weight of all the asteroids must be considerably less than the weight of Mars, for otherwise their gravitational attractions would produce disturbances in the orbit of Mars. It seems probable that the total weight of all the known asteroids is less than the one-thousandth part of the weight of the Earth.

We do not know what was the origin of this swarm of tiny planetary bodies. They may represent the debris of a planet which exploded long ago, or they may be the remnants of matter out of which the planets were formed, that has never aggregated into a single body. There does not seem to be any way by which either of the possibilities can be definitely proved or disproved, and we must therefore leave the question of their origin as an unsolved problem.

Passing through the zone of the minor planets we come to the largest and most massive of all the planets, Jupiter. As we have seen above, when considering Bode's Law, its distance from the Sun exceeds five times the Earth's distance. Jupiter's year is nearly twelve of our years, and its velocity in its orbit round the Sun is rather less than half the velocity of the Earth, or about 9 miles per second. Both in volume and in weight Jupiter far exceeds all the other planets combined. It is so large that it could contain more than 1,300 bodies of the size of the Earth. In proportion to its size, it is not so massive as the Earth. Jupiter is 317 times heavier than the Earth; but if it were composed of the same materials as the Earth, it would weigh about four times as much as it actually does. The average density of the material of which it is composed is only about 30 per cent. greater than the density of water. The reason for this low mean density we shall see presently.

The velocity of escape from Jupiter is very high, about 40 miles per second. We should consequently expect to find that Jupiter has an exten-

sive atmosphere; even the fast-moving molecules of hydrogen are not able to escape from the strong binding power of Jupiter's gravitation. The telescope confirms our anticipations, for we can see nothing of Jupiter's surface, but merely atmospheric formations that are continually changing. In the telescope, Jupiter is seen to be distinctly flattened. This is evidence of rapid rotation, for, if it were not rotating, its gravitation would have pulled it into a spherical shape. Jupiter rotates more rapidly than any other planet, the length of the day being rather less than 10 hours. The year on Jupiter therefore contains about 10,000 Jovian days. If the markings revealed by the telescope are observed for a few hours, they will be seen to be moving across the planet's disc, giving direct proof of the rotation. More exact observation shows that different zones of the planet rotate at different speeds, the equatorial portion of the planet having the most rapid rotation. This provides confirmation that we do not see the solid surface of the planet.

The markings occur in zones which are approximately parallel to the equator (Plate IX). The equatorial zone is usually very bright and is bordered to the north and south by two darker brownish zones. Numerous small, well-defined, bright and dark spots are frequently observed in these two zones; these spots, which must be some sort of cloud phenomenon, though their nature is still a mystery, sometimes last for several months. There is one remarkable marking which has persisted for many years. It is known as the Red Spot. When first seen in 1878, it appeared as a pale pinkish oval spot.

It rapidly developed in size, changing to a brick-red colour, until it stretched over a length of about 30,000 miles and had a breadth of about 7,000 miles. It was then about equal in area to the whole of the surface of the Earth. Though it faded considerably in subsequent years, it remained a conspicuous object until about 1919, when it gradually became less conspicuous. It can still be seen, though it is no longer a prominent object. The spot does not remain in a fixed position; during the last 30 years it has drifted to as great a distance as 20,000 miles on each side of its mean position and through several thousand miles in latitude. It has been suggested that the spot was produced by an eruption of some sort, possibly volcanic in origin, and that the ejected gases poured out over the highest cloud zone and remained in practically a stationary position relative to it. The drifting of the spot to and fro could then be explained by currents in the atmosphere of Jupiter. But in the light of new knowledge about the constitution of Jupiter, this explanation does not seem probable. It is noticeable that the red spot is less conspicuous on photographs taken in infra-red light than in photographs taken in ultra-violet light, and this seems to point to a position in the upper regions of Jupiter's atmosphere. The cloud-layer on Jupiter is so thick that infra-red photographs completely fail to penetrate it.

Planetary observers were formerly of the opinion that the rapidity of the changes which occur on Jupiter was an indication that the planet was hot. On account of the great distance of Jupiter from the Sun, the amount of heat which falls on each square

foot of Jupiter is only one-twenty-seventh of that which falls on each square foot of the Earth, so that Jupiter could only be hot if it had a large internal store of heat. There were various theoretical considerations which made it difficult to accept this. When direct measurement of the temperature of Jupiter became possible, it was found that it was extremely cold; the observed temperature is about 200° F. below zero, far lower than any experienced in the Earth.

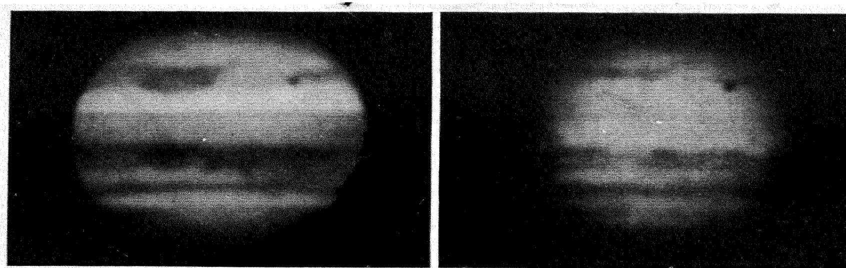
Bearing this extremely low temperature in mind, it will be evident that the clouds in the atmosphere of Jupiter cannot be composed of water-vapour or even of particles of snow or ice. By the analysis of the light from Jupiter, which is, of course, reflected sunlight, two constituents of its atmosphere have been detected—ammonia, the pungent gas which is used in many refrigerating plants, and methane, or marsh-gas, the gas produced by vegetable matter decomposing under water, and known to the coal-miner as the dangerous fire-damp.

This provides the key to the interpretation of the atmosphere of Jupiter. We believe that Jupiter, together with the other planets, was formed from matter ejected by the Sun. It is known that the Sun consists largely of hydrogen. We may suppose, therefore, that Jupiter, when it was first formed, contained a large proportion of hydrogen. Unlike the Earth, it was able to retain the hydrogen because of its large gravitational attraction. As it cooled down from its initial hot state, the oxygen in its atmosphere combined with some of the hydrogen and formed water-vapour which, when the planet had cooled

still further, was deposited as a thick layer of ice. Nitrogen and carbon also combined with some of the excess hydrogen to form saturated compounds. The most volatile compounds of hydrogen with nitrogen and carbon are ammonia and marsh-gas respectively; these are therefore the gases that we should expect to find in the atmosphere of Jupiter. It may be remarked that the presence of these substances in the atmosphere of Jupiter is in itself conclusive proof that Jupiter cannot be hot, for, if it were, they would be dissociated into their constituent elements. Even at low temperatures the ultra-violet radiation from the Sun gradually breaks up the molecules both of ammonia and of marsh-gas; but in the absence of oxygen the break-up is followed by a natural recombination. We thus have a further proof of the absence of oxygen. From the quantity of ammonia observed to be present in the atmosphere of Jupiter, Dunham has deduced that the temperature cannot be lower than about 185° F. below zero, if it can be assumed that the atmosphere consists mainly of hydrogen. This is in good agreement with the measured temperature, when the difficulties of the observation are considered.

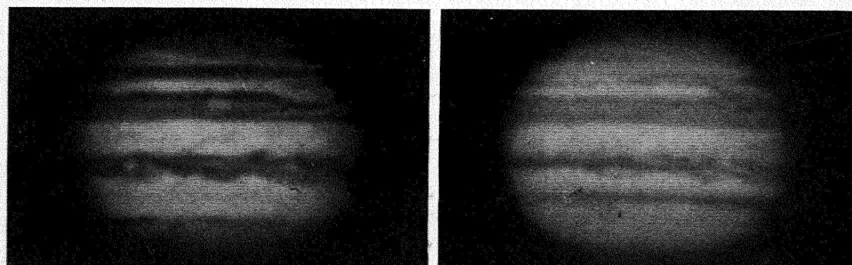
Our conclusion that the solid surface of Jupiter must be covered with a thick coating of ice was suggested several years ago by Dr. Jeffreys, before we had any positive information about the constitution of the atmosphere of Jupiter. From various theoretical considerations, it has been concluded that the real Jupiter—which is not what we see in the telescope—is a solid body with an average density about equal to that of the Earth. This rocky core occu-

pies about one-eighth of the whole volume of Jupiter. It is covered with a thick ice layer measuring some 16,000 miles (twice the diameter of the Earth) in thickness. Outside this glacier coating there is a very extensive atmospheric layer about 6,000 miles deep. It is only the outer layer of this atmosphere that we see in the telescope and from which we draw our conclusions as to the size of Jupiter. The great depth of this atmosphere has some interesting consequences. The pressure at the bottom of it is so enormous—many thousands of tons to the square inch—that the gases are entirely liquefied. Higher in the atmosphere the substances which are the most refractory to liquefy, such as helium and hydrogen, will exist as gases; the more easily liquefied constituents will still be liquid. In this atmosphere at these great pressures peculiar things can happen. If, for instance, a mixture of hydrogen and helium is subjected to great pressure the hydrogen will liquefy while the helium still remains as a gas; but the compressed helium is heavier than the liquid hydrogen, and so it sinks below it, and we have the strange phenomenon of the liquid hydrogen floating on the helium gas. Probably there are analogous conditions for other gases in other regions of the atmosphere. It will be readily understood that an atmosphere consisting of a mixture of gases and liquids will be extremely unstable and violent disturbances will occur in it. The changes that we see occurring on Jupiter are probably due to these disturbances. The Red Spot may be caused by some commotion of this sort rather than by volcanic action. The immense thickness of the glacier



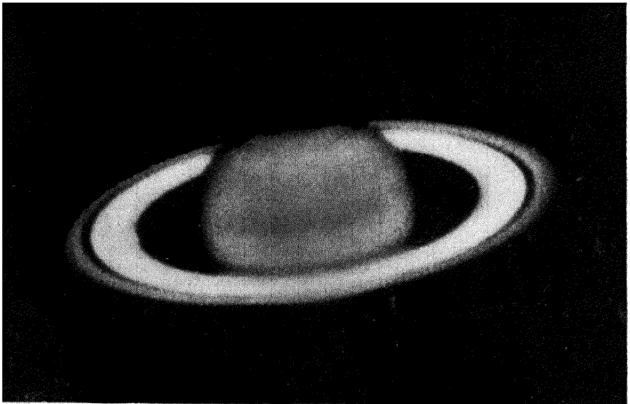
(*a*) JUPITER, PHOTOGRAPHED IN ULTRA-VIOLET AND INFRA-RED LIGHT.

The red spot is the oval dark marking in the upper portion of the left-hand photograph. The small black spot in each photograph is the shadow of one of the satellites thrown by the sunlight on to Jupiter.

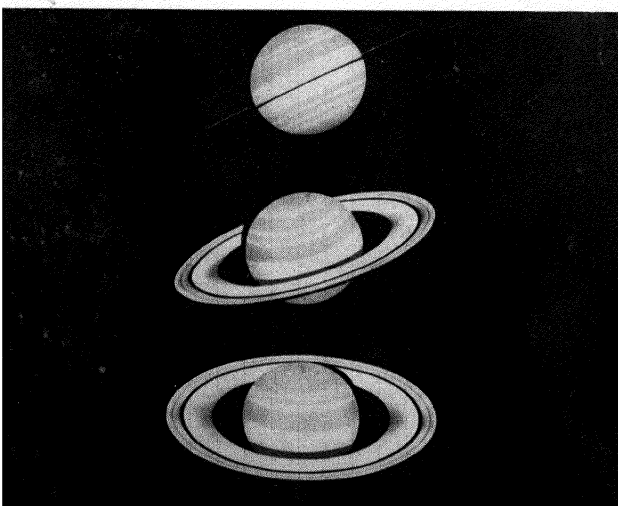


(*b*) DIFFERENT ASPECTS OF JUPITER.

PLATE IX.



(*a*) SATURN WITH ITS SYSTEM OF RINGS.



(*b*) DIFFERENT ASPECTS OF THE RINGS OF SATURN, DEPENDING UPON THE POSITION OF THE EARTH WITH RESPECT TO THE RINGS.

PLATE X.

coating would seem to make volcanic action impossible.

The outer gaseous atmosphere of Jupiter above the cloud layer, containing hydrogen, ammonia, marsh-gas and other gases, is probably only a few hundred miles in thickness. The low mean density of Jupiter, not much greater than that of water and less than that of any rock, now appears in its true perspective, for it is not the true mean density of the solid rock core but an average value for the solid core, the ice layer and the deep atmosphere.

Jupiter appears to be a singularly uninviting world, with its glacier-covered surface, its biting cold and its particularly unpleasant atmosphere of hydrogen, pungent ammonia and pestilential marsh-gas. Its cloudy layer probably consists largely of minute particles of frozen ammonia; the rays of the Sun never penetrate through it, so that the glacier surface of Jupiter is in perpetual darkness. Even though conditions were otherwise suitable for mankind, its strong gravitational pull would have unpleasant consequences. A man who weighs 13 stone on the Earth would weigh more than 34 stone if he were transported to Jupiter; he could move about only with great effort and would be in serious danger of collapsing under his own weight.

Jupiter has a wealth of satellites: nine are known and a tenth has recently been suspected. The four brightest were discovered by Galileo in 1610—one of the first-fruits of the invention of the telescope. These four major satellites, which are named Io, Europa, Ganymede and Callisto, are easily seen with the aid of a pair of field-glasses. Their positions

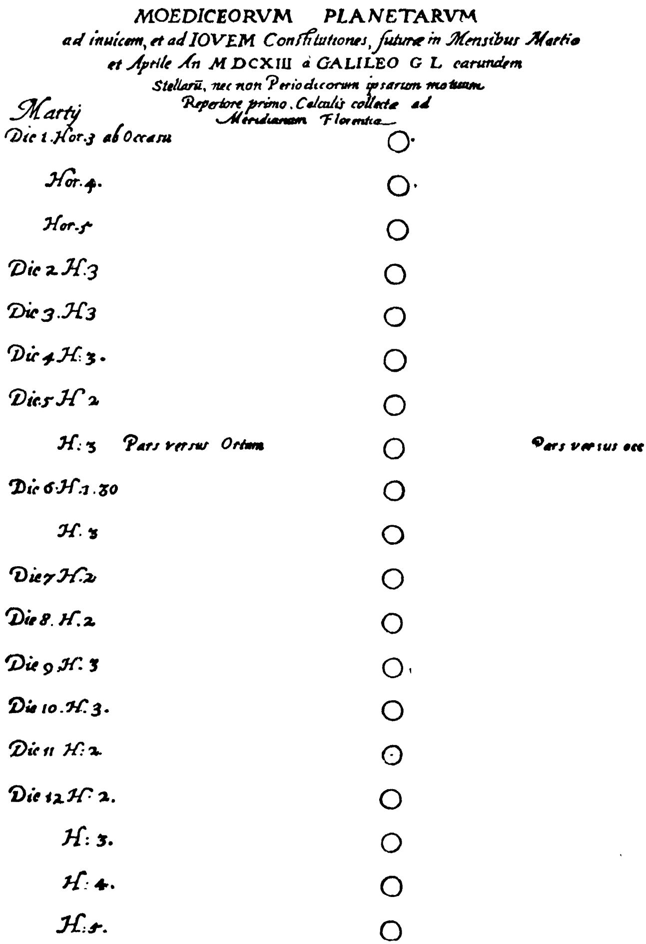


FIG. 2.—Observations of Jupiter's satellites by Galileo. (From *Istoriae Dimostrazioni intorno alle Macchie Solari*, 1613.)

with respect to Jupiter change from night to night; the changes in position can easily be followed with field-glasses, the configurations each evening being given in *Whitaker's Almanack.* Some of Galileo's observations of the movements of the satellites are reproduced in Fig. 2. Ganymede and Callisto are the largest satellites in the solar system; they are rather larger than Mercury but weigh appreciably less. Callisto has only one-quarter of the weight of Ganymede and its average density is only six-tenths that of water; it probably consists largely of ice and solid carbon dioxide. Io and Europa are comparable to the Moon in size, and both they and Ganymede appear to be masses of rock, like the Moon. It is unlikely that any of these satellites has an atmosphere. The remaining five satellites are small bodies with diameters probably ranging from about 15 to 100 miles.

The other planets can be passed over rather briefly. Saturn is Jupiter's smaller brother, the second largest planet in our system. Its volume is more than 700 times that of the Earth, or somewhat more than half that of Jupiter; for its size its weight is low, being only 95 times that of the Earth, so that its average density is only seven-tenths that of water, less than that of any other planet. The velocity of escape from Saturn is 24 miles a second, so that Saturn has not lost its atmosphere. The low average density can be accounted for by supposing that the atmosphere is very extensive. As in the case of Jupiter, the disc of the planet shows markings in the form of belts which run in zones more or less parallel to the equator (Plate X). They are less

sharply defined and less variable than those of Jupiter, but they are certainly atmospheric and not surface markings. Occasionally well-defined spots are seen. A large bright spot appeared in August 1933, which rapidly grew until it extended over 15,000 miles. It remained visible for several weeks; its appearance suggested that a mass of dust had been thrown up by an eruption on the planet and that the ejected matter was carried forward by winds in the upper atmosphere, while still being fed from below.

Saturn is the most flattened of all the planets. The equatorial diameter is 76,000 miles; the polar diameter is only 68,000 miles. This suggests rapid rotation. As in the case of Jupiter, the rotation is more rapid near the equator than in higher latitudes. A complete rotation at the equator takes about $10\frac{1}{4}$ hours, so that Saturn rotates rather more slowly than Jupiter. The planet is even colder than Jupiter because of its greater distance from the Sun, and the composition of its outer atmosphere appears to be generally similar to that of Jupiter, except that ammonia is less in evidence and marsh-gas is relatively more prominent in the atmosphere of Saturn than in that of Jupiter. As ammonia is more easily condensed than marsh-gas, the low temperature of Saturn has caused most of the ammonia to condense out of its atmosphere. Without making any observations, we could have predicted that there would be less ammonia in the atmosphere of Saturn than in that of Jupiter.

Saturn has the same general constitution as Jupiter—a solid core of rock, overlaid by a thick

glacier coating and surrounded to a great height by a dense atmosphere of compressed gases. But the atmosphere of Saturn is relatively much more extensive than that of Jupiter. The depth of the atmosphere of Jupiter is only about one-seventh of the whole radius of the planet, whereas the depth of the atmosphere of Saturn is nearly half the whole radius. The solid core is about 28,000 miles in diameter, or approximately 3½ times the diameter of the Earth. This is covered with a coating of ice some 6,000 miles in depth and then above this the atmosphere extends for a further 16,000 miles. The total weight of this atmosphere is about equal to the weight of the rocky core. It is because the atmosphere of Saturn is relatively much more extensive than the atmosphere of any of the other planets that the average density of Saturn is so low.

The system of rings which surround Saturn makes it unique and one of the most beautiful objects to be seen in a telescope. The rings lie in the plane of the equator and extend to a distance of 85,000 miles from the centre of the planet. Their thickness is extremely small in comparison with their width, and is probably not more than about 10 miles. Because of this small thickness, the rings become quite invisible when the Earth passes through the plane of the rings and they are edgewise on to us. The disappearance of the rings was a puzzle to Galileo. In 1610 he had noticed an appendage on either side of the planet, but the poor definition of his small telescope did not permit him to recognise the true nature of the rings. After a while he noticed that the appendages had disappeared, but a few years later they

were again visible. The true explanation of the appendages was given by Huyghens in 1655. Different aspects of the rings are illustrated in Plate X.

The rings are composed of a swarm of small fragments, which move round Saturn in nearly circular orbits. Clerk-Maxwell proved mathematically in 1856 that the rings could not be either solid or liquid, because in either case they would break up into a large number of small portions forming, as it were, a swarm of little moons each moving round Saturn under the influence of its gravitational pull. There is no doubt that the rings actually do consist of such a swarm of small moons. As in all cases of bodies moving round a parent body under the compelling force of its gravitation, the rule of the road is that the fastest moving parts take the innermost traffic lane and the slowest moving take the outermost lane. In 1895 Keeler obtained direct observational proof that the ring system consists of such a swarm. By means of the spectroscope he was able to detect the rotation of the rings and to show that the inner edge rotates more rapidly than the outer. If the rings were solid we should find exactly the opposite, for the outer portion would then be moving more rapidly than the inner. It occasionally happens that Saturn passes in front of a bright star; when this occurs the star can be seen through the rings, dimmed in brightness but never disappearing completely.

The rings were produced by the disruption of a satellite of Saturn which came too near to Saturn and paid the penalty. It came so close that the mighty pull of Saturn split it into pieces. These

pieces, colliding with one another, were still further broken up until at length the fragments were scattered in a ring all round Saturn. If any satellite comes within a certain distance of its parent body, the tidal forces exerted on the satellite are so great that it must break up. This can be proved mathematically, and it is of interest to note that the rings of Saturn lie within the danger limit, but that in no other case do any of the satellites of the planets in the solar system come inside the danger zone within which disruption is likely to occur.

Collisions between the separate fragments of which the rings are composed must be numerous. When two fragments collide, their velocities are changed and they have to seek the traffic lanes appropriate to their new speeds. In doing so, still more collisions take place. But the swarm as a whole goes moving on. The numerous collisions must result in a continuous shower of fragments falling on to Saturn. Thus Saturn is not only extremely cold, with an unpleasant atmosphere, but it is also subject to a continual bombardment from these fragments: it is certainly a world which we should avoid if we were desirous of seeking for a new habitation.

In addition to the rings, Saturn has a wealth of satellites; nine are known, equal in number to Jupiter's system. The largest is appropriately called Titan and is intermediate in size between our own Moon and Mercury. The others are considerably smaller, though larger than the five small satellites of Jupiter. Little is known about the physical conditions of any of these bodies; they are almost

certainly devoid of any atmosphere and probably all keep the same face continually towards Saturn.

The Sun, as seen from Saturn, would appear much smaller than it does to us, but it would be intensely bright. Most of the moons would appear considerably larger than the Sun, though they would not have its brilliancy. The view from Saturn, of the nine moons of different sizes, circling round at varied speeds, and of the rings, stretching as a vast silvery arch across the sky, must be a fascinating spectacle.

The next two planets, Uranus and Neptune, are very similar to one another. Much smaller than either Jupiter or Saturn, they are considerably larger and heavier than the Earth, having about sixty times its volume and sixteen times its weight. Volume for volume, they are therefore much less massive than the Earth. They are too far away for the telescope to reveal very much; we should expect such massive planets to possess considerable atmospheres, and the spectroscope confirms this. We again find very strong evidence of marsh-gas which, apart from hydrogen, is probably the principal constituent in their outer atmospheres. The Sun's radiation at such great distances is very feeble, and both planets are consequently extremely cold. It is because they are so cold that no traces can be found of ammonia, which is so prominent a constituent of the outer atmosphere of Jupiter. There is probably plenty of ammonia on both Uranus and Neptune, but it is condensed out of their atmospheres and exists only in the liquid or solid form. Their low mean densities suggest that their atmospheres

must be very extensive; the depth of the atmosphere of Uranus is probably about 3,000 miles, and of that of Uranus is about 2,000 miles. As in the case of Jupiter and Saturn, both planets are covered with a glacier coating which is some 6,000 miles in thickness.

Uranus was the first planet to be discovered, for Mercury, Venus, Jupiter and Saturn have been known from time immemorial. It was found by William Herschel—musician by profession, but astronomer by inclination—on March 13, 1781, with a 7-inch reflecting telescope which he had constructed himself. Herschel found it by chance in the course of a systematic survey of the entire visible heavens in which he was engaged. He noticed that it had a different appearance from a normal star. A star appears only as a point of light in a telescope, but this object showed a definite disc. That he had found a new planet did not occur to him; he described it in his astronomical journal as a "curious either nebulous star or perhaps a comet." When it was found to be moving relatively to the stars it was thought to be a new species of comet, without any tail. Herschel named it the Georgium Sidus, in honour of the King, George the Third. Further observations proved it to be a new planet, nearly twice as far from the Sun as Saturn. The name Uranus finally adopted for it was suggested by Bode.

After the path of Uranus in the sky had been calculated, it was found on looking back through earlier observations that Uranus had been observed many times previously, the earliest observations being one

by Flamsteed, first Astronomer Royal, in the year 1690. But the quality of the early telescopes was so poor that the difference in the appearance of Uranus and of a star had not been noticed. These earlier observations served a valuable purpose. They not only helped to provide material from which a more accurate orbit of Uranus could be computed than would otherwise have been possible until after an interval of many years, but they also revealed unexpected discordances between the observed positions and the computed positions at these times.

It occurred at about the same time to two young astronomers, J. C. Adams in England and Leverrier in France, that there might be an unknown planet which was exerting a gravitational pull on Uranus and causing it to deviate from the expected path. On July 3, 1841, Adams, whilst still an undergraduate at Cambridge, made this note: "Formed a design, in the beginning of this week, of investigating, as soon as possible after taking my degree, the irregularities in the motion of Uranus, which are yet unaccounted for, in order to find whether they may be attributed to the action of an undiscovered planet beyond it, and, if possible, thence to determine approximately the elements of its orbit, etc., which would probably lead to its discovery." A first solution of this problem Adams attempted in 1843, and in September 1845 he communicated his final results to Professor Challis, at the Cambridge Observatory. Challis set out to find the unknown planet by determining the positions of all the stars in the suspected region, and investigating whether

any one of these showed evidences of motion. Challis made his observations faster than he could map them, and had already observed the unknown planet twice without realising it when it was discovered by Galle at Berlin. Leverrier had completed his investigations a few months later than Adams, and he wrote to Galle, at the Berlin Observatory, requesting him to search for a new planet in exactly the same region of the sky in which Adams had asked Challis to search. The Berlin astronomers had the advantage of a new star chart covering this particular region of the sky; all they had to do was to compare the chart with the sky and see whether there was an interloper in the sky which was not shown on the chart. Within half an hour of commencing the search, on September 23, 1846, Galle found such an interloper and further observations the next night showed that it was moving amongst the stars and confirmed its planetary character. Thus Adams and Leverrier can justly share the honour of the discovery of Neptune.

Both Adams and Leverrier had assumed, for the purpose of their calculations, that the distance of the unknown planet was the distance to be expected according to Bode's Law. This proved later to be incorrect, Neptune being the first planet to show a serious departure from Bode's Law. Consequently, the shape of the orbit and the mass of Uranus, which they predicted, were considerably in error. Nevertheless, the investigations gave, with sufficient accuracy, the direction of the new planet from the Sun during the time covered by the bulk of the observations of Uranus. The direction in which

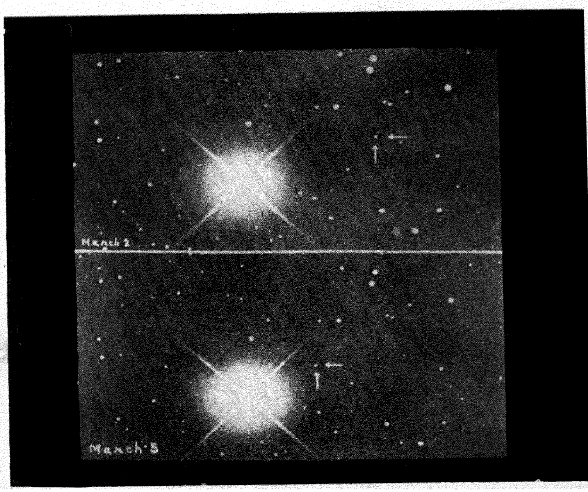
telescopes should be pointed to find the new planet was correctly indicated, and this enabled the planet to be found, which was the main purpose of their investigations.

Uranus possesses four rather small satellites; two of these were discovered by William Herschel, a few years after he had discovered Uranus; the other two were found by Lassell in 1851. Lassell had already in 1846 discovered the single satellite of Neptune; this is brighter than any of the satellites of Uranus, though it is at a considerably greater distance from the Earth. It must be a body of some size, probably larger than the Moon and about equal in size to Mercury or to the two largest satellites of Jupiter.

The most distant member of the solar system, Pluto, was discovered in January 1930 by Tombaugh at the Flagstaff Observatory. The history of the events which led to this discovery is of some interest. There remain small discordances between the observed and the computed positions of both Uranus and Neptune, after the disturbing effects of the other known planets are allowed for. These are no doubt due, in part at least, to the shapes of the orbits of these two planets not being known with absolute accuracy; it must be remembered that Neptune was discovered only in 1846, and, as Neptune takes nearly 165 years to go once round its orbit, it has not completed one revolution since discovery. It was, however, possible that the discordances might be due in part to the disturbing action of an unknown planet more distant than Neptune. A detailed mathematical investigation

(*a*) Photograph showing Stars and Three Minor Planets.

The images of the stars are round. The images of the minor planets are drawn out by their motion into short streaks or trails.



(*b*) Photographs of Pluto, March 2 and March 5, 1930.

The two arrows point to the image of Pluto. The change in the position of Pluto, arising from its orbital motion round the Sun, will be noticed.

Plate XI.

was made by Lowell in the year 1915. He derived an orbit for the hypothetical unknown planet and concluded that its weight was about $6\frac{1}{2}$ times that of the Earth, or rather less than half the weight of Uranus.

The planet was anticipated to be faint, and a search was made by photographic methods in the region of the sky in which Lowell's calculations indicated that it should be. The new planet was discovered as the direct result of this search. In Plate XI, two photographs, obtained at Flagstaff in March 1930, at an interval of 3 days, are reproduced. The bright star is Delta Geminorum, and the motion of Pluto, relative to the stars, in the 3 days is easily apparent. Further investigations have shown that the weight of Pluto is much smaller than Lowell had estimated. Instead of weighing $6\frac{1}{2}$ times as much as the Earth, it has probably less than one-tenth the weight of the Earth. Further observations will be required before any more definite statement can be made. It is certain that a planet so small in weight will produce such minute deviations in the paths of Uranus and Neptune that they will be swallowed up in the errors of observation. In other words, Pluto could not have been predicted. That a planet should be found where Lowell's investigation indicated that a planet should be looked for is one of those happy coincidences which sometimes occur. Some time ago a new faint comet was discovered; the large telescope at the Yerkes Observatory was set to observe the comet, and there it was, right in the centre of the field. But it was then discovered that an error had

been made in setting the telescope and that a new, hitherto unknown comet had been found! Probabilities are entirely against such happenings: nevertheless, they sometimes occur.

Pluto must be a small planet, probably smaller than the Moon. It is therefore unlikely to have any atmosphere. Its temperature must be so low (probably about $-230°$ C.) that all but the most refractory gases would be liquefied or even solidified. If it is not mere barren rock, it must be covered with a layer of ice, solid carbon dioxide, ammonia, nitrogen and other substances. The mean distance of Pluto from the Sun is about 3,675 million miles, but its orbit is more elongated than that of any other major planet, so that the actual distance can vary by as much as 920 million miles. The distance to be expected according to Bode's Law is about twice the mean distance, so that this empirical law—which was much in error for Neptune—is completely wrong for Pluto. The time which Pluto takes to travel once round its orbit is about 248 years. The mean velocity in the orbit is about 3 miles a second, less than one-tenth of that of Mercury.

The small size of Pluto suggests that it may really be more akin to the minor planets than to the planets proper, and it is possible that other bodies will be found at about the same distance, forming an outer zone of small planets. The discovery of these small distant worlds will not be easy, because of their faintness. Until such other bodies may be found or until we have more accurate knowledge of the size and weight of Pluto, it is rather idle to speculate.

It is of interest to enquire what the Sun and other planets would look like from Pluto, the most remote known member of the solar system. The Sun would appear smaller than Jupiter appears to us when at its nearest, and would therefore not show a visible disc. The intensity of its light would be about 300 times that of the Full Moon on the Earth. The Sun would therefore appear very much brighter than any star and would look somewhat like an intensely brilliant arc-light in the sky; the intensity of the sunlight on Pluto would be about equal to that of a 500 candle-power lamp at a distance of 10 feet, and so there would be plenty of light for the purposes of everyday life—if life could exist on such a world. Neither Mercury, Mars, Uranus nor Neptune could be seen from Pluto with the naked eye; Venus and the Earth would be visible in the absence of the Sun, but as they would always be within about 1° from the Sun, they could not be seen. Jupiter and Saturn would never be more than 7° and 14° respectively from the Sun and could therefore only be seen very shortly after sunset or before sunrise: Jupiter would appear as a star of about the fourth magnitude and Saturn as a star of about the sixth magnitude, so that neither would be very conspicuous in the sky of Pluto. Pluto is thus not a desirable observation post for the investigation of the solar system.

CHAPTER IV

LIFE IN OTHER WORLDS

A QUESTION that I am often asked is whether life exists in other worlds, either on one of the other planets belonging to our own solar system, or possibly on a planet belonging to some other Sun. Before attempting to give an answer to this question, some assumptions must be made. The forms of life which have evolved on our Earth are forms which are presumably adapted to the varied conditions which are found on the Earth—or beneath the ground or in rivers and seas. It is conceivable that life may exist under conditions that differ widely from any of which we have experience. Yet it is difficult to believe that there can be life of any sort on a world that is entirely devoid of an atmosphere or on one that has an atmosphere containing no oxygen. Water is probably also essential. Nor does it seem probable that life can exist under great extremes of temperature—either intense heat or intense cold, though we should be rash if we attempted to state limits of temperature outside which life could not exist.

Given that conditions on any world are such that life is possible, can it be assumed that life must necessarily exist there? The conditions under which life can exist may not necessarily be conditions under which it is possible for it to originate. We really know nothing about when or how life began on our

Earth. It is believed that the Earth and the other planets condensed out of a long filament or tongue of matter drawn out of the Sun by another star passing near it. Whether or not this theory of the birth of the planets is correct in detail, it seems reasonably certain that the planets of the solar system were formed in some way out of the Sun.

In the beginning there could have been no life on the Earth or on any of the other planets, for no life is possible on the Sun. The temperature of the Sun is so high that all but a few of the simplest chemical compounds are broken up into the constituent atoms. A single living cell is a complicated structure from the chemical point of view and could not exist on the Sun.

At some time, then, in the past history of the Earth—a history which we have already seen extends back somewhere about three thousand million years—life first made its appearance. Geologists have found primitive marine invertebrates in rocks of the Archean period, of an age of about 1,300 million years. Life may therefore have appeared comparatively shortly after a solid crust formed on the Earth. Are we to suppose that life developed spontaneously, because conditions were suitable for it, or that its appearance was due to a special act of creation on the part of the Creator? If we adopt the latter viewpoint, further discussion becomes superfluous, and for the sake of argument we assume that life developed spontaneously. As to the conditions which may be necessary for such spontaneous development we can perhaps argue that—since no biologist has ever succeeded, even with all

the resources of modern laboratory technique, in producing life of any sort—a delicate balance between various factors is essential before life will appear.

If this is so, the way to further discussion is again blocked because we are in ignorance as to the conditions in which life will originate. All we are able to do is to enquire whether conditions elsewhere in the Universe are such that life could exist, recognising the limitation that even though conditions on any world are suitable for the support of life, it does not necessarily follow that life exists on that world.

Considering the solar system, it seems probable that we can at once rule out of consideration most of the planets and all of their satellites. Mercury appears to be entirely devoid of any atmosphere; moreover, the temperature of the face which is turned to the Sun is about the temperature of molten zinc, whilst the night face of the planet, in the absence of any atmosphere, must be extremely cold. Jupiter and Saturn have very extensive atmospheres, but both observation and theory agree in indicating a complete absence of oxygen and water-vapour. The outer atmospheres of these planets apparently consist predominantly of hydrogen, ammonia and marsh-gas. The atmospheres are many thousands of miles in depth and the pressures in their lower portions are so great that the gases are mostly liquefied. We cannot conceive that life can be supported under such conditions, even if the intense cold on the planets did not by itself make life impossible. Conditions are even more extreme

on Uranus and Neptune; there is a greater degree of cold, and in the outer atmospheres marsh-gas is more prominent than ammonia merely because the ammonia cannot remain gaseous at such low temperatures. Pluto is a small body, probably without any atmosphere and with a temperature so low that neither nitrogen nor oxygen could exist on it in a gaseous condition. We cannot regard it as at all probable that any form of life, either vegetable or animal, could exist on any of these worlds.

Is it possible that life may exist on one or other of the larger satellites in the solar system? We can at once disregard all the small satellites, because they must long ago have totally lost their atmospheres. We have seen that our own Moon is a dead world, completely devoid of any atmosphere. The only other satellites which perhaps demand some consideration are the two largest satellites of Jupiter, Callisto and Ganymede, and the largest satellite of Saturn, Titan. The two satellites of Jupiter are not very different in size from Mercury, but they are considerably less massive. Ganymede weighs rather more than half as much as Mercury. Callisto, though about equal in size to Ganymede, has less than one-third of its weight. The pull of gravitation at the surface of either of these satellites is therefore less than at the surface of Mercury. It follows that the velocity of escape from each of these satellites is lower than the velocity of escape from Mercury. We should not therefore expect to find any atmosphere on either of them. Direct observational evidence seems to support this; the surfaces

of both satellites can be seen, and spectroscopic observations give no evidence of any atmosphere on either. Similar remarks apply to Titan; it is smaller and not so massive as Mercury, and there is no indication of any atmosphere.

Venus and Mars remain for consideration. Venus keeps her secrets well guarded. Her face is permanently hidden from us by a thick layer of cloud which even the haze-penetrating infra-red rays cannot pierce. Neither oxygen nor water-vapour has yet been detected in her atmosphere. But we cannot at present regard the failure to detect them as absolutely conclusive proof of their absence. It may be that the clouds on Venus extend to such a great height in her atmosphere that the sunlight is reflected back from them before it has had the opportunity to pass through a thickness of atmosphere great enough for the absorption by oxygen or water-vapour to be of sufficient amount to be capable of detection by the tests which are at our disposal. These tests are not capable of detecting very small amounts of either oxygen or water-vapour.

The clouds presumably provide direct evidence of the presence of water-vapour; the failure to detect water-vapour above the cloud-layer is probably due to all the water-vapour having been condensed out of the upper atmosphere.

The only positive information as yet obtained about the atmosphere of Venus is a definite proof of the presence of carbon dioxide. This is present in much larger amount in the atmosphere of Venus than in our own atmosphere. The amount of car-

bon dioxide above the cloud-layer is so considerable that it is possible with some justification to argue that the failure to detect oxygen is really due to its total or almost total absence. We should expect to find both water-vapour and carbon dioxide present on a cooling planet of the size of Venus. As the molten rocky mass cooled and began to solidify, large quantities of water-vapour, carbon dioxide and other gases would be evolved from it. When the surface had cooled sufficiently, the water-vapour would condense and oceans would cover much of the surface; the atmosphere would contain the inert gases, nitrogen, argon and neon, and a large amount of carbon dioxide. It is unlikely that oxygen would be present at this stage in any appreciable amount; most terrestrial volcanic rocks are incompletely oxidised and, if free oxygen had been present in the Earth's atmosphere when the crust solidified, these rocks would have greedily laid hold upon it. The present abundance of oxygen in the Earth's atmosphere is probably due to the action of vegetation, which steadily extracts carbon dioxide from the air and returns oxygen in its stead. The carbon dioxide supply is in turn replenished by processes such as respiration, combustion and the decay of vegetable matter. Life on the Earth probably started at a time when the atmosphere contained comparatively little oxygen and was in the form of primitive vegetable life. The vegetable life, as it developed, gradually increased the amount of oxygen in the atmosphere, and conditions at length became suitable for animal life. Venus is apparently at a stage which the Earth passed through millions of years

ago, having an abundance of carbon dioxide but little, if any, oxygen.

So far as the temperature of Venus is concerned, conditions are probably favourable. Though warmer than the Earth, it is not excessively warmer; there is probably a hot, humid climate which, provided only that free oxygen is present in sufficient quantity, should be quite capable of supporting life. There is nevertheless the possibility that the blanketing effect of the carbon dioxide in the atmosphere may raise the temperature at the surface very considerably, and in the equatorial regions even to the boiling-point of water. Conditions suitable for life might therefore develop first in the polar regions.

What type of life there may be if it exists we can only hazard a guess. On the Earth we find the extremes of climate within which it seems possible for the human race to exist. Is this the result of chance, or is it not rather the result of evolution, conditioned by the prevailing physical conditions? The conditions on Venus now are possibly not greatly unlike the conditions which prevailed on the Earth at an earlier stage in its history, when the climate was warmer and more humid than it now is and when vast swamps covered the Earth. If so, it is possible that a form of life adapted to such conditions, somewhat akin to the swamp-dwelling mammoths which once lived on our Earth, may have evolved on Venus.

The balance of evidence would seem, however, to be in favour of the view that the amount of oxygen in the atmosphere of Venus is not at present

sufficient for the support of any life, except possibly primitive vegetable life.

We know more about Mars than about Venus because we can see its surface. We have found that Mars possesses a thin atmosphere, in which both oxygen and water-vapour may be assumed to be present. The atmosphere is scanty, it is true, the amount of oxygen being considerably less than on the Earth. We know that man can become acclimatised in a short time to live at considerable heights, in a very thin atmosphere, and it is quite conceivable that, by the process of evolution, forms of life may have developed on Mars which can exist in the attenuated atmosphere of that planet. A great impetus to the belief that Mars may be inhabited by a race of intelligent beings was given by the publication of Professor Lowell's book entitled *Mars as the Abode of Life.* Lowell studied the surface of Mars under the exceptionally favourable climatic conditions, and at the high altitude of the Flagstaff Observatory in Arizona. He observed a large number of the fine straight markings which had been discovered by Schiaparelli and named "canals" by him. He found that the canals covered the surface of the planet in a complex network, forming a fairly regular geometrical design. Many of them extended for thousands of miles. At various points, called *oases* by Lowell, several canals intersected. The oases are darker regions which may cover a large area of several thousand square miles. There is no doubt as to the existence of these darker patches or oases. Many of the canals were believed by Lowell to be double, appearing as two

fine equidistant lines, somewhere about one or two hundred miles apart. From a study of many drawings of the planet, Lowell concluded that the canals changed their appearance with the Martian seasons. Usually faint or invisible during the spring, they gradually become more prominent as the polar cap shrinks, appearing to grow towards the equator at a rate of some fifty miles a day, and often extending beyond the equator well into the opposite hemisphere. This appearance gradually fades away and then, half a Martian year later, the canals are again seen to be growing towards the equator, but this time they are extending from the opposite polar cap.

Lowell interpreted these observations as providing evidence of the activities of a race of intelligent beings who were engaged in a desperate struggle for existence on an arid world, where there was little or no rainfall. He supposed that the canals were artificial channels constructed to bring water from the melting polar caps towards the equator, for purposes of irrigation, in regions where there was little or no rainfall, and he believed that the darkening of the canals was due to water flowing along them. The oases were interpreted as large irrigated areas; here were to be found the centres of population, the inhabitants being driven from the arid regions by the scarcity of water.

Lowell asserted that some of the canals disappeared for several years at a time and new canals appeared where none had previously been seen. This was apparently due to some of the canals silting up from time to time and after a lapse of years being

opened up again, or even to new canals being constructed.

To cover a planet with a network of " canals," or water channels, each of which must be at least fifty miles wide, extending for hundreds or thousands of miles, would be an immense undertaking, which might not unfairly be attributed to a race of beings in a higher state of civilisation than our own. Such was Lowell's opinion. The theory is a fascinating one, if only we could be certain that the canals are really there !

But another equally skilled observer, Professor Barnard, possessed of remarkable acuity of vision, who had, moreover, the advantage of years of observations with some of the largest telescopes in America, was unable to see the fine geometrical network of lines described and drawn by Professor Lowell. At times Barnard could see " short, diffused, hazy lines, running between several of the small very black spots which abound in this region of the planet." Observing Mars with the great 60-inch reflector at the Mount Wilson Observatory in California, Barnard said that it gave him " the impression of a globe whose entire surface had been tinted a slight pink colour, on which the dark details had been painted with a greyish coloured paint, applied with a very poor brush, producing a shredded or streaky and wispy effect in the darker regions."

Such differences between competent observers are probably to be attributed to complex psychological factors. The observer gazes intently at a highly magnified image of the planet; the detail which he

strives to see is at the limit of vision. The slightest tremor in the atmosphere is magnified by the telescope, with the result that the image becomes somewhat unsteady. For a moment it settles down, if conditions are of the best, to an almost perfect image; but before the eye can see the fine detail, another tremor has spoilt the image. Faint details which the eye has seen momentarily (and the surface of Mars is certainly rich in fine detail) the mind tends subconsciously to connect by straight lines. The final picture, though as faithful a representation as the observer can draw, may bear but a faint resemblance to the real object or even to the picture drawn by another observer. We may compare the early drawings of some of the spiral nebulæ by Lord Rosse with modern photographs of the same nebulæ (Plate XXX). The spiral structure of these nebulæ was discovered by Lord Rosse with his great 6-foot reflector about 1850. Though the spiral structure is certainly there, a comparison of the details of the drawings and photographs shows little resemblance; the spiral formation is not nearly so much in evidence in the photographs as in the drawings.

The balance of astronomical opinion is against the objective reality of the system of canals depicted by Lowell. If we do not accept the objective reality of the canals, we must also abandon his graphic picture of the race of intelligent beings struggling desperately for existence. In answer to the question whether Mars is inhabited, we can only point to probabilities. We have seen that the atmosphere of Mars, though rather rare, could probably support life. The conditions as regards temperature,

though not very pleasant, are not such as to make life impossible. Near noon, in the equatorial regions, the temperature rises to about 50° F.; but in the afternoon, as the Sun gets lower in the heavens, it rapidly falls and after sunset the cold becomes intense, the minimum temperature at night probably reaching 130° F. below zero. This enormous daily range of temperature and the rapidity of the changes must prove very trying for any form of life.

It would seem probable that such life as may exist must protect itself from the bitter cold at night by taking refuge in caves or holes in the ground. Vegetable life is most likely to be in the form of lichens or mosses.

Our conclusion is that life of any sort is unlikely to exist anywhere in the solar system, apart from our own Earth, except possibly on Venus or Mars. Conditions on neither of these planets appear particularly favourable, but, in view of our present incomplete knowledge of these conditions, the possibility of life cannot be ruled out. The conditions on Venus may be compared with those on our Earth many million years ago; those on Mars are perhaps similar to those that will prevail on the Earth many million years hence, when the Sun is cooler than it is now and when our oxygen supplies may have been largely used up.

The possibility of life elsewhere in the Universe than in our solar system remains for brief consideration. We can only deal with probabilities, for we have no means of detecting whether any of the stars, other than the Sun, has a system of planets; if such systems exist, we can never know

anything about the actual physical conditions which prevail on them. It seems probable that planets are only born when two stars pass so close to one another that enormous tides are raised on their surfaces; great jets of matter are then drawn out of each star, which break up and finally condense into a system of planets.

This theory of the origin of a planetary system is not without its difficulties, but for want of any more plausible theory we may accept it provisionally. It would seem to imply that the birth of planets must be an event of extremely rare occurrence. On the basis of the random wandering of the stars, as we find them distributed in the neighbourhood of the Sun, a sufficiently close approach of two stars can happen on the average only about once in every five thousand million years.

This argument was a valid one before the expansion of the Cosmos had been discovered. But it is now known that the Cosmos is expanding at such a rate that in about 1,300 million years the distance of any one stellar universe from any other universe is doubled. It may be thought that this is an extremely slow rate of expansion. But when we consider that our Earth is some 3,000 million years old, it will be seen that when it was born distances were less than one-quarter of what they are now, provided that we can assume the expansion to have been uniform in the meantime. It is therefore more than probable that close approaches of two stars were formerly far more frequent than they are now. In that case, there must have been a progressive diminution in the birth-rate of planets. In our

Universe, which contains about 200 thousand million stars, it may consequently be regarded as not improbable that there are many stars—even though an extremely small percentage of the total number —which have planetary systems.

But even when this possibility is granted, life is not likely to develop on any planet unless there be a suitable combination of various factors. The planet must be at such a distance from its parent Sun—whose output of radiation in the form of heat and light may be either very much greater or much smaller than the output from our Sun—that its temperature is neither too high nor too low. It must be of sufficient size and weight to be able to retain its atmosphere; it is probably necessary that it should not be so large and massive as to retain the hydrogen which would initially predominate, for then the whole of the oxygen would be likely to combine with some of the hydrogen to form water, leaving an atmosphere entirely devoid of oxygen. Conditions suitable for the support of life are not likely therefore to prevail in more than a small proportion of planetary bodies.

Our own Universe is one of many millions. It is estimated that, up to the distance to which the most powerful telescope yet made can probe, there are some 75 million universes, generally comparable in size and in other respects. There must then in the Cosmos as a whole be many millions of stars with families of planets belonging to them. Though we cannot make any definite assertion, it is reasonable to suppose that conditions on some at least of these must be such that life is possible. If we can assume

that life will appear when conditions are suitable for it, the balance of evidence must be in favour of the conclusion that the probability is that there are many other worlds scattered through the Cosmos on which life exists.

COMETS AND SHOOTING STARS

THE motions of the planets are known with such accuracy that we can predict in what part of the sky Jupiter or Mars or any other planet will be found in a hundred years' or in a thousand years' time. But there are other members of the solar system whose appearance cannot generally be predicted; these members are comets and shooting stars. We shall see that there is a reason for considering the two types of object together.

From the very earliest ages, comets and shooting stars have attracted widespread attention. Shooting stars were thought to be stars which had dropped from the sphere on which all the stars were supposed to be fixed and had fallen to Earth. Comets were also believed by many primitive people to be stars with a long hairy tail: the word " comet " means hairy star. In the old Chinese records the appearance of comets and new stars are mixed up together, and it is not possible in many cases now to decide whether the record refers to a comet or to a new star. But Aristotle and his followers thought that comets were exhalations from the Earth, which had caught fire in the upper regions of the atmosphere. This view is not really so surprising as it may now seem to us. The tail of a comet is longest and the comet itself is at its brightest when it is nearest to the Sun. The comet can then be seen only shortly

after sunset or before sunrise and, since the tail of a comet always points in the direction away from the Sun, the comet will then be seen with its tail pointing upwards and appearing like a rising flame, the head of the comet possibly being below the horizon and therefore invisible.

It is not surprising that these strange apparitions, appearing suddenly and at rare intervals, were regarded as omens of misfortune, the harbingers of famine, pestilence, wars or the impending "death of Princes."

> "*When beggars die, there are no comets seen,*
> *The Heavens themselves blaze forth the death of*
> *Princes,*"

says Calpurnia in *Julius Cæsar*. For a great comet, with its tail blazing forth like a great fiery arch across the sky, is a magnificent spectacle, and it is easy to understand how people, ignorant of the true nature of a comet, could be terrified by so unusual a sight. Many instances of the association, in the popular mind, of the appearance of a comet with a tragedy or misfortune could be mentioned. One will suffice. Daniel Defoe in his *Journal of the Plague Year* mentions how much the alarm in London was increased, when the great plague of the year 1665 was in its early stages, because a blazing comet had appeared some weeks earlier. This comet was of a "dull, languid colour" and its "motion very heavy, solemn and slow," the interpretation being that "a heavy judgement, slow but severe, terrible and frightful, was already begun." In 1666, a little

before the Great Fire, another comet appeared "bright and sparkling or, as others said, flaming, and its motion swift and furious," portending a judgement "sudden, swift and fiery." He mentions that many remarked "that those two comets passed directly over the city, and so very near the houses that it was plain they imported something peculiar to the city alone."

Comets, like the planets, move round the Sun under the controlling force of the Sun's gravitational attraction. But whereas the planets move in orbits which do not in general differ very much from circles, the orbits of comets are usually extremely elongated. A comet is in general only visible during the portion of its path in which it is nearest to the Sun. The speed of the comet is greatest when it is at its nearest to the Sun because the comet, like the planets, obeys Kepler's Law of Equal Areas (p. 39); it therefore rushes very quickly round this portion of its orbit, and as it moves away from the Sun its speed becomes slower and slower. So though a comet may take several hundred years to go once round its orbit, the time during which the comet is visible may be only a few weeks or months.

It used to be thought that a comet appeared, moved past the Sun, and disappeared, never to return again. The proof that a comet may return and be seen again was due to Halley. He found that the paths of the bright comets which had appeared in the years 1531, 1607 and 1682 were almost identical. He concluded that it was the same comet which had appeared in these three years, and that the bright comets seen in the years

1456 and 1305 were also the same comet. At the end of his account he added, "Hence I think I may venture to foretel, that it will return again in the year 1758." Halley died in the year 1742. Little attention had been paid to his prediction at the time, but it gradually began to be realised that the return of the comet, in accordance with this prediction, would provide a remarkable vindication of Newton's law of universal gravitation. As the time for the return drew near there was great excitement among the philosophers of the age. On Christmas Eve, 1758, the comet was seen by a farmer in Saxony and Halley's prediction was triumphantly verified.

Halley's comet is the most famous of all comets. Records of its appearance at every return back to the year A.D. 989 have been found and, with a few gaps, it has been traced back to the second century B.C. Josephus recorded "a fiery sword hanging over Jerusalem" at the great siege in 170 B.C., an omen foretelling the destruction of Jerusalem. This was Halley's comet. The comet appeared in March 1066, and men thought it predicted the success of the Norman invaders; the English were frightened and the Normans encouraged by this sign in the heavens. In the famous Bayeux tapestry, made by Queen Matilda to celebrate the victory of her husband, there appears a representation of the comet and of the wonder and dismay of the people (Fig. 3). Over the picture is the legend "Isti mirant stella." In 1456 the comet was of extraordinary brilliancy, its tail stretching half-way across the sky; in that year Constantinople was taken by Mahomed II, who proceeded to advance westward into Europe

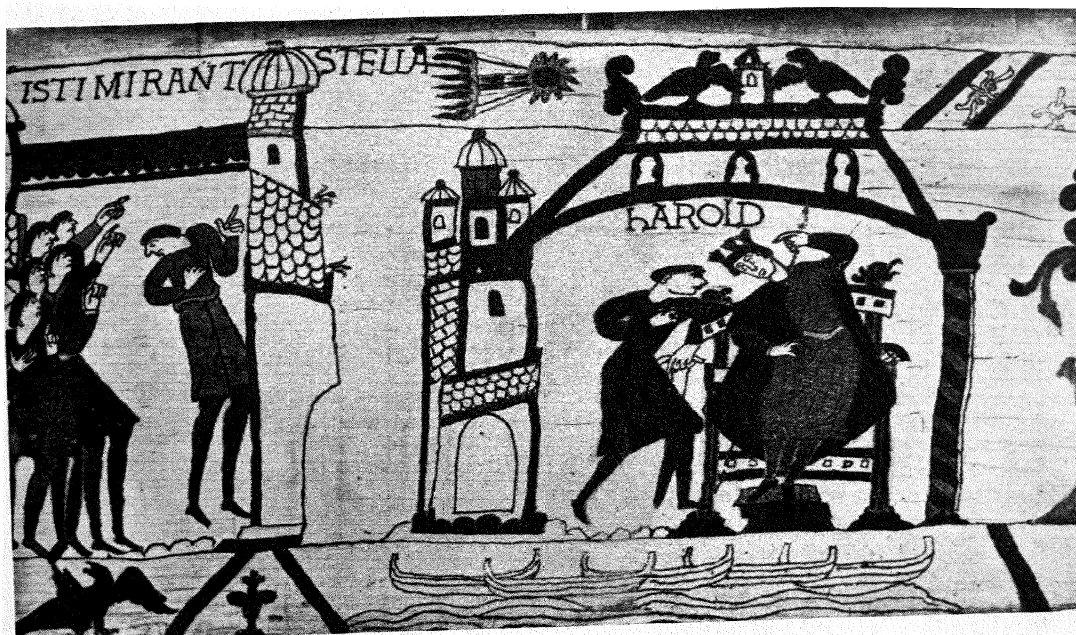


FIG. 3.—Halley's Comet, from the Bayeux Tapestry

and to spread terror throughout Christendom. The most recent appearance of the comet was in the year 1910; it was not then favourably placed for observation in England, but was a magnificent spectacle in the southern sky.

Many other periodic comets, as a comet which returns again is called, are known. Perhaps the most famous is Encke's comet, which was first seen in 1786 and returns every $3\frac{1}{2}$ years. Not a single return since its discovery has been missed, but the comet is not a striking object in the sky and can only be seen with the aid of a telescope. Sometimes a comet in the course of its wanderings happens to pass very near to Jupiter or Saturn; these massive planets then pull the comet out of its path and may entirely change the shape and size of its orbit. A comet, known as Brooks's Comet, which used to take 30 years to travel round its orbit, passed very near to Jupiter in 1886, and the gravitational attraction of Jupiter was so great that the direction of motion of the comet was changed to such an extent that it now takes only 7 years to complete its orbit.

Not all comets are periodic comets in the sense that they have been observed at more than one return. It is nevertheless probable that every comet will return in time, though the orbits of many are so extremely elongated that several hundreds or even thousands of years may be taken by the comet in going once round its path. We might perhaps think that there may be comets wandering about in space and having no connection with the solar system; if such is the case, occasionally one of these comets may come under the influence of the Sun's gravita-

tion and be drawn towards the Sun. The comet will then pass near the Sun and may or may not be captured, depending upon its speed and the closeness of approach. If not captured, it will go off again into space, never to return. We have no certain evidence, however, that any comet of which we have record has ever come from outside the solar system in this way. They all appear to be permanent members of the system.

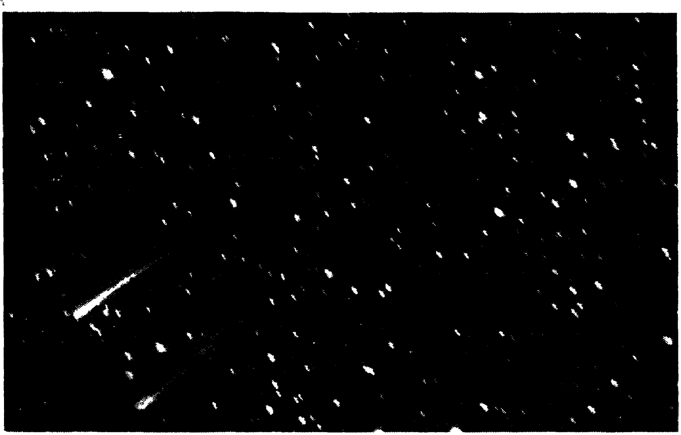
Before we attempt to answer the question "What is a comet?" we must describe the appearance of a typical comet. When at a considerable distance from the Sun, and visible only in a telescope, a comet usually appears as a faint nebulous or hazy cloud in which a central brighter condensation or nucleus may sometimes be seen. No tail is visible at this stage. As the comet approaches the Sun, this head or coma takes on a more clearly defined outline, but it never becomes absolutely sharp. The nucleus usually appears as a bright star-like point near the centre of the coma, though sometimes no nucleus can be seen. The photograph of Halley's comet reproduced in Plate XII shows the coma and its nucleus. From the coma there now begins to stream out a nebulous-looking tail (or tails, for some comets have several distinct tails); the tail seems to spring from the nucleus and its brightness decreases rapidly with distance from the nucleus. As the comet gets still nearer to the Sun, the tail grows in length and becomes brighter. The structure of the tail is often very complicated and liable to rapid changes. The tail is always directed *away* from the Sun, as though it is repelled by some force emanat-

(*a*) Halley's Comet (1910), showing Nucleus and Head.
In taking the photograph, the telescope has followed the movement of the comet and the star images have been drawn out into streaks.

(*b*) Brooks's Comet (1911).
The structure of the tail is very complex.

Plate XII.

(*a*) MOREHOUSE'S COMET (1908).



(*b*) BROOKS'S COMET (1903).

Two photographs, taken with an interval of 24 hours, have been superposed to show that the tail does not stream behind the comet along the direction in which the comet is moving.

PLATE XIII.

ing from the Sun. It does not therefore follow the comet, like smoke from an engine, and the popular idea of a comet as a star with a tail of fire trailing behind it is entirely erroneous. Some photographs taken by Professor Barnard show the effect well. He obtained two photographs of a comet at an interval of 24 hours; during this interval the comet had time to move appreciably. He then combined the two pictures so that the stars on the one fell exactly on the corresponding stars on the other. The combined picture is reproduced in Plate XIII; the movement of the head of the comet in the interval between the two photographs is clearly shown, but it will be noticed that the tail does not point along the direction in which the comet is moving.

In 1843 a bright comet appeared which came to within 80,000 miles from the Sun. It was then moving with a tremendous speed of several hundreds of miles per second and swung half-way round the Sun in about a couple of hours. The tail was at least 300 million miles in length and as the comet swung round the Sun the end of the tail moved with a speed considerably greater than half the speed of light; such a speed is almost in itself sufficient to prove that the tail could not be a rigid appendage of the comet.

The tail of a comet consists of minute particles of matter which are blown out from the nucleus by the pressure of the radiation from the Sun. When light falls on any body, it exerts a pressure upon it just as the waves of the sea press against any obstacle on which they impinge. The more intense the light the greater the pressure. The pressure of light was

first predicted theoretically by Clerk-Maxwell and was subsequently demonstrated by delicate experiments in the laboratory. We shall see later that the pressure of radiation plays an extremely important rôle in the interiors of stars, where the intensity of the radiation is very high. The nearer a comet approaches to the Sun, the stronger is the radiation falling upon it and the greater the pressure. Every small particle in the head of the comet is acted upon by two opposing forces—the pressure of radiation which is trying to blow the particle away and the gravitational pull of the comet which is trying to hold it back.

Suppose that for a particle of a certain size these forces are just balancing one another; now let us consider what will happen in the case of a particle of half the linear dimensions. The pressure of radiation has only one-quarter of the surface to act on and is therefore one-fourth of the pressure on the larger particle. But as the smaller particle has only one-eighth of the weight of the larger, the gravitational pull of the comet is less in the same proportion. It is clear that for this particle, therefore, the pressure of radiation will be twice as great as the pull of gravitation and the particle will therefore be blown out of the head, in the direction away from the Sun. There will consequently be a continuous stream of minute particles blown out from the comet.

What happens as the comet moves round the Sun can be imagined by thinking of the analogy of a spray of water coming out of the nozzle of a hose as the hose is swung round. The particles of water

are continuously moving along the spray and the spray is being continuously fed from the nozzle. We see also why the tail of a comet grows as the comet nears the Sun and becomes smaller again as the comet recedes; this is a direct consequence of the greater intensity of the Sun's radiation when the comet is nearest to the Sun.

Comets differ very much in the size of their heads and of their nuclei. The heads themselves may be very large. The head of the celebrated comet of 1811 was larger than the Sun. The nucleus is usually not more than a few hundreds of miles, or in exceptional cases a few thousand miles across. The tail often extends over many millions of miles, with a volume many times greater than that of the Sun. It is surprising therefore to find that the weights of comets are insignificant—judged, of course, not by terrestrial standards but in comparison with the weights of the planets. We have mentioned that sometimes a comet will pass so near to a planet that the pull of the planet on the comet entirely alters its path; yet it has never been possible to detect any effect of the pull of a comet on a planet. It is probable that the weight of every comet is less than a one-millionth part of the Earth's weight; even so, the comet may weigh many millions of tons.

The weight being so small and the head frequently large, the average density of matter in the head must be very small—probably of the order of the density of the residual air in a chamber exhausted by a good air-pump. The average density in the tail must be much smaller even than this. Ten

thousand cubic miles of tail will not contain more matter than one cubic inch of ordinary air. It is not surprising, therefore, that when a comet passes in front of a faint star, the star may be seen shining through the head without any perceptible diminution in brightness. We must not suppose that the head of the comet actually consists of a very attenuated gas. If a comet were gaseous, its gravitational pull would not be sufficient to hold it together against the tendency of a gas to diffuse outwards in all directions, and the comet would be rapidly dissipated away into space. The head is a loose collection of rocks, stones and smaller particles which may range in size from large masses weighing millions of tons to the very finest dust, the larger masses being widely separated from one another.

In May 1910, Halley's comet passed directly between us and the Sun at a distance of about 15 million miles. The tail was at least 20 million miles long and was pointing directly towards us, so that we probably passed through it. Some alarm was caused by the publicity given to this passage, because the spectra of comets show the presence of the very poisonous gas, cyanogen. But so attenuated is a comet's tail that we had no indication at all that the Earth was passing through the tail. Astronomers examined the Sun carefully to detect the passage of the head of the comet across its face, but no trace of it could be seen. As the head is mainly empty space, this was not at all surprising.

A few years ago, in June 1921, the Earth escaped collision with Pons-Winnecke's comet by a few days only. Such a collision, if the comet were a large

one, would be serious for the region of the Earth where the impact occurred. But for a comet of an average small size the effects would be relatively local. In Arizona there is a cup-shaped crater about a mile across and 600 feet deep which was formed by the collision of either a small comet or of a very large meteor with the Earth. Many pieces of meteoric iron, of all sizes up to lumps weighing a few tons, have been found within an area extending to a distance of several miles from the crater.

Occasionally a comet is seen to split up into two or more fragments. In 1889 Brooks's comet was observed to split up into two portions, which slowly separated; the disruption was apparently a result of the comet passing very close to Jupiter. Biela's comet provides another example. This comet was discovered in 1826; it proved to be a periodic comet with a period of about $6\frac{3}{4}$ years. At the return in 1846, it had the appearance of a normal comet when it was first seen, but shortly afterwards it divided into two parts which gradually separated from each other. In 1852 the twin comets appeared again, but by then their separation had greatly increased. Neither comet was ever seen afterwards, though they were looked for at successive returns. But in 1872, when the Earth passed the track of the lost comet, there was a fine display of shooting stars. Whenever the Earth passes through the track of the vanished comets, this display is observed, but not always with the same brilliancy. What has happened is that the comet has completely disrupted and the fragments have become scattered along its orbit.

The most famous of all meteor showers is the Leonid shower, which appears about the middle of November. On November 13 and 14, 1866, there was a particularly brilliant display when many thousands of shooting stars flashed across the sky, radiating out in all directions from a definite centre. Frequently, several could be seen at the same instant, and many left bright luminous trails which lingered in the sky for several minutes. These meteors follow the track of the great comet of 1866, which has disintegrated. It takes this swarm about 3 years to pass any given point, but $33\frac{1}{3}$ years to go completely round its orbit, so that the fragments of this comet have not yet become by any means uniformly spread round the orbit.

The appearance of the ordinary shooting star is caused by a solid fragment of matter entering the Earth's atmosphere at a high speed. As the meteor moves rapidly through the atmosphere, a cap of air forms in front of it and becomes heated by friction with the surrounding air through which it passes. The heat is communicated to the surface layers of the meteor itself, which become vaporised. The envelope of heated air and vaporised material may trail behind the meteor and leave a luminous streak persisting for several seconds. A meteor is usually first seen when it is at a height of about 80 miles above the surface of the Earth, and remains visible until the height has decreased to about 50 miles. The length of the path may be as great as several hundred miles, but the apparent length of the path in the sky depends upon the direction in which the meteor is moving. If it is moving towards us, the

path will appear short and the motion slow, but if moving across the line of sight, the path will appear long and the motion rapid.

The average shooting star is very small ; the range in size is probably from a pea to a grain of sand. These small bodies become completely vaporised in their passage through the atmosphere and never reach the ground. It is fortunate that the Earth has a protective atmosphere, for otherwise the effects produced by small meteors moving with a speed many times greater than that of a rifle bullet would be serious. It has been estimated that the total number of meteors which enter the Earth's atmosphere in the course of a day is several millions; many of these would pass harmlessly by, if our Earth had no atmosphere, but a sufficient number would reach the surface to be distinctly unpleasant for us.

When the Earth crosses the track of a disrupted comet, each fragment entering the atmosphere appears as a shooting star and we have what is called a meteor shower. Most of the isolated shooting stars are caused by particles which do not belong to the solar system, but come from outer space and enter the Earth's atmosphere with velocities frequently greater than 60 miles a second.

Some of the fragments may be larger than the small particles which appear as the typical shooting star. We may then have the appearance of a fireball—a brilliant ball of light, easily visible in broad daylight, which is usually dissipated in an explosion or a series of explosions of considerable violence, to the accompaniment of a loud report. Fragments

may then fall to Earth as meteorites. Meteorites frequently weigh many tons and usually consist of masses of limestone, magnesia or siliceous stone, generally mixed with globules of iron. A small percentage of meteorites consist of nearly pure iron.

The greatest meteor fall of recent years occurred on June 30, 1908, in a remote part of Siberia, near Vanovara on the Stony Tunguska River, about 700 miles north of Lake Baikal. There was little information available about the details of the fall until an expedition under Professor Kulik was sent by the U.S.S.R. Academy of Sciences in 1927 to investigate the locality. The actual place in which the meteorite fell was a crater-like valley. It was found that in this valley and on the surrounding hills all the vegetation had been burned. The trees in the surrounding forests to a distance of about 20 miles had been blown down by the blast of wind when the meteor fell; they had all fallen outwards from the place of fall so that, when seen from a height, the forest presented a fan-like appearance. The trees had been stripped of their bark and most of their branches were scorched as though by the heat from an enormous furnace. In the valley were found dozens of deep funnel-shaped holes, marshy at the bottom, varying in diameter from several yards to about 50 yards. Each of these probably contains a meteorite, though the nature of the ground made it impossible to recover any. About one thousand reindeer are said to have been killed, but the loss of human life was slight, the fall occurring in a thinly populated region. Reports collected

by the expedition from eye-witnesses of the fall tell of the appearance of a fiery flame, considerably brighter than the Sun, giving off great heat, and of a violent explosion followed by a tremendous cannonade, like loud thunder and guns firing, which lasted for about five minutes. One native, whose hut was said to be at three days' march from the place, had his hut knocked down, the top blown away by the wind, his brother stunned and his reindeer scattered. Professor Kulik considers that the total weight of the meteorite was about 130 tons and that the meteor, in falling, carried the cap of heated incandescent gas in front of it right down to the ground. When the meteor struck the ground, the heated air was driven violently outwards in all directions, felling the trees over a wide area and blasting the nearer ones. The aerial waves produced by the fall travelled outwards at a speed of about 11 miles a second and were recorded by microbarographs in England, nearly 4,000 miles away from the fall, and in America, at a distance of about 6,000 miles. Brilliant green, gold and crimson twilight hues were seen in England on the night of the fall and for several subsequent nights; they were caused by fine dust carried high up into the atmosphere by these waves. Seismic waves of the earthquake type were produced by the impact and, travelling through the Earth, were recorded on seismographs up to distances of about 3,000 miles from the fall.

It is perhaps surprising that records of meteor falls are not more numerous, and that there are very few known instances of damage caused by such falls.

On February 9, 1913, a slow procession of some hundreds of bright meteors was seen to pass across Canada and over the Atlantic Ocean to near Bermuda, where they struck the sea. The meteors passed in groups, some containing 20 to 40 meteors, others only 3 or 4, with their tails streaming out behind. One observer, awed by the sight, remarked that they must be "souls going to heaven." This stream of meteors was possibly the final display of some worn-out comet of past ages.

On July 19, 1912, a shower of meteoric stones fell near Holbrook in Arizona. The meteor before falling made a loud booming noise that was heard some 40 miles away, though in broad daylight the meteor itself was not visible. The falling stones were seen, however, raising puffs of dust from the dry sand of the desert. Upwards of 14,000 fragments were subsequently collected over an area about 3 miles long by half a mile wide, some buried to a depth of several inches; the total weight of these fragments was about a quarter of a ton.

CHAPTER VI

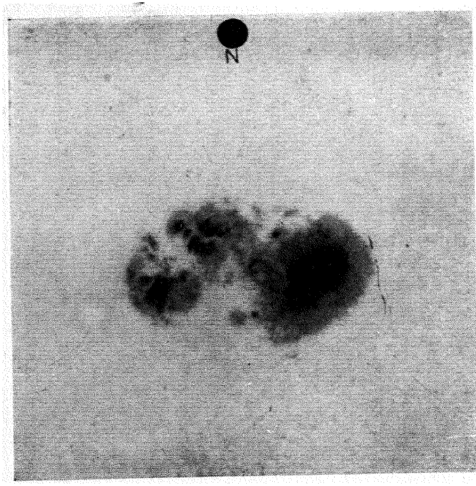
THE NEAREST STAR—THE SUN

THE Earth and the Moon, the planets and their satellites and the comets—the bodies which we have so far considered—are the children of the Sun. They are all under his tutelage, constrained by him to follow their allotted courses and dependent upon him for such light and heat as they receive. The Sun is a much larger body than any of the planets. We have seen that the largest of the planets, Jupiter, when its extensive atmosphere is taken into account, has a volume about 1,300 times that of the Earth; the Sun, however, could contain about 1,000 bodies of the size of Jupiter, or about 1,300,000 bodies the size of the Earth. If the Earth were placed at the centre of the Sun, the orbit of the Moon, which is at a distance of nearly one-quarter of a million miles from us, would be contained entirely within the Sun and would be little more than half-way out to the surface. In proportion to its size the Sun is much less massive than the Earth; it is on the average less than one and a half times as dense as water, or about one-quarter as dense as the Earth.

This low average density suggests that the Sun must be largely gaseous. If we look at the Sun through a suitably darkened glass, its surface appears uniformly bright; but when the Sun is photographed we find that the brightness falls off rapidly as the edge or limb of the Sun is reached. This is a proof

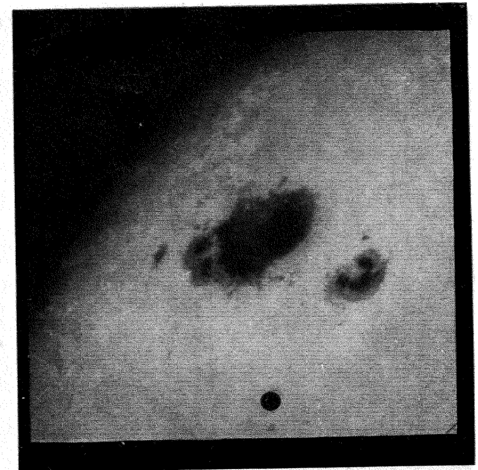
that the surface of the Sun is gaseous and not solid or liquid; the light reaching us from the central portion of the disc passes through a lesser thickness of the cooler outer layers of the Sun's atmosphere than the light from near the limb. The actinic light of short wave-length is scattered in the Sun's atmosphere much more than the light of longer wave-length in the visual region of the spectrum; that is why the falling off in brightness towards the limb is much more noticeable in photographs than it is visually.

If we could get sufficiently near to the Sun, we should probably see one or more dark spots on its surface. These are called "sun-spots." The largest sun-spots can be seen without difficulty with the naked eye. The best time to look for a large spot is when the Sun is near the horizon, as its brightness is then much reduced; at other times, the Sun must be looked at through dark or smoked glass, to protect the eyes from injury. There are many old Chinese records of sun-spots, but the real interest in them dates from the year 1610, when Galileo studied them with his primitive telescope. He found that the spots changed their positions on the disc of the Sun from day to day, and at first thought that they were planets, seen projected on the Sun. But continuing his observations, he noticed that some of the spots were of irregular shape and that the shape changed from day to day. A reproduction of one of Galileo's drawings (from his *Istoria e Dimostrazioni intorno alle Macchie Solari*, published in 1613) is given in Fig. 4; in this drawing, B, C are developments of the spot A, and E, F, G, H, L are developments of the



(a) LARGE SUN-SPOT, JULY 31, 1906.

The Earth is shown on the same scale. The area of this spot is 1,720 million square miles, nearly nine times the total surface area of the Earth.



(b) LARGE GROUP OF SPOTS NEAR THE SUN'S LIMB, JANUARY 20, 1926.

The large spot has an area of 4,000 million square miles. It is the largest spot which has appeared on the Sun during the last 60 years. The passage of the spot across the disc gave rise to a severe magnetic storm on the Earth.

PLATE XIV.

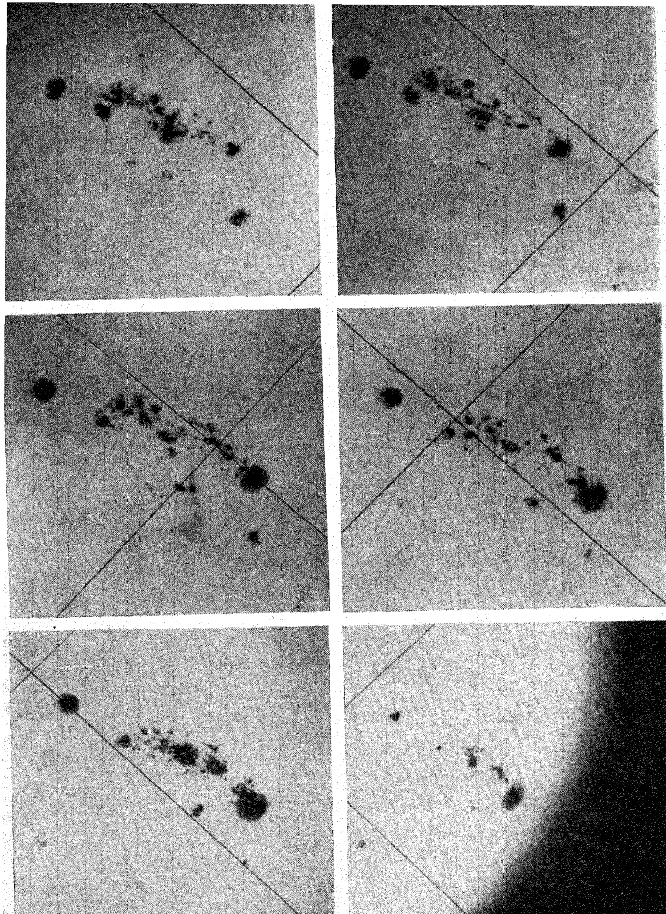


PLATE XV.

SERIES OF PHOTOGRAPHS SHOWING MOTION OF GROUP OF SPOTS ACROSS THE DISC OF THE SUN, CAUSED BY THE SUN'S ROTATION.

Note the changes from day to day in the structure of the group (March 19–25, 1920). The centre of the visible disc of the Sun is approximately defined by the intersection of the two black lines. Each photograph shows only a small portion of the disc.

spot D. Galileo therefore came to the conclusion that the spots were really markings of some sort on the surface of the Sun.

The apparent movement of the spots across the face of the Sun was correctly interpreted by Galileo as a consequence of the rotation of the Sun about its axis; the rotation causes the spots to appear to move along tracks parallel to the Sun's equator. The movement of a large group of spots across the Sun is illustrated in Plate XV. As with Jupiter and Saturn, the period of rotation is not the same for all parts of the surface. One complete rotation takes about 25 days at the Sun's equator, but the period increases steadily as we go towards either pole, where it is about 34 days. This affords further proof that the Sun is not solid.

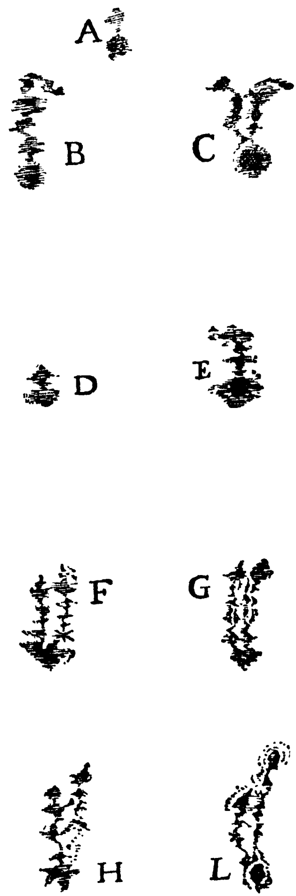


FIG. 4.—Observations of sunspots by Galileo. (From *Istoria e Dimostrazioni intorno alle Macchie Solari*, 1613.)

A spot may appear and grow with great rapidity and may last for several months. But most spots

have a life of only a few days. A normal fully developed spot consists of a dark central region, called the *umbra*, with a lighter *penumbra*, in which a radial fibrous structure may be seen. The umbra appears black only by contrast with the much brighter surface of the Sun around it. If we could shut off the light from the rest of the Sun, we should find the spot to be intensely bright. A very large spot may have an umbra which is 50,000 miles across and a penumbra which is 150,000 miles across. The area of the umbra of such a spot is about 10 times the area of the whole of the surface of the Earth and the area of the penumbra is about 80 times the Earth's surface. Photographs of typical large spots are reproduced in Plate XIV.

The spots on the Sun were assiduously studied for nearly 50 years, from 1826 onwards, by Schwabe, an apothecary of Dessau. Every day that the Sun was visible at Dessau, Schwabe observed it with his telescope and made a record of the spots that he saw. In 1843 he was able to announce that there was a periodicity in the appearance of the spots; during the years 1828 to 1831 there were only a few days on which no spots were visible, but in 1839 no spots were to be seen on 139 days. From 1836 to 1840 there were in all only 3 days on which he saw no spots, but in 1843 there were 149 days. His further observations confirmed his first announcement of a periodicity. The frequency of appearance of the spots fluctuates in a period of about 11 years; this period is not, however, absolutely constant. During the present century sun-spots were numerous in the years 1905, 1917

and 1928, and infrequent in the years 1901, 1913, 1923 and 1933. At the present time the number of spots is increasing and the next maximum may be expected in 1938 or 1939.

A similar periodicity is shown by certain terrestrial phenomena, amongst which we may mention the aurora borealis or australis and magnetic storms. The aurora does not appear with equal frequency each year but shows a regular fluctuation with a period of about 11 years, the same period as that of the sun-spots. Not only is the period the same; there is a direct correlation between auroræ and sun-spots. Auroræ are frequent when sun-spots are numerous and infrequent when the spots are scarce. The same direct correlation is shown by magnetic storms; when a magnetic storm occurs, a compass needle, instead of pointing steadily in one direction, oscillates wildly to and fro and telephone and telegraph circuits may be put out of action. It does not necessarily follow that either the aurora or the magnetic storm has any direct connection with a particular sun-spot or even with sun-spots in general. All that we can assert is that periodic changes of some sort are occurring within the Sun and that the fluctuation in the numbers of sun-spots is one manifestation of these changes; the appearance of auroræ and the occurrence of terrestrial magnetic storms must be dependent upon and caused in some way by these changes in the Sun.

A sun-spot is a gigantic funnel-shaped vortex in the outer regions of the Sun. Around the vortex intensely hot gas from within the Sun is whirling spirally upwards. We can compare a sun-spot

vortex with the hollow vortex formed by water emptying out of a bath, if we imagine the water to be made to run in the opposite direction and to stream upwards from the outlet into the bath. As the gases stream out of the funnel-shaped mouth of the vortex, the pressure which has urged them upwards is released; they expand rapidly and are considerably cooled as a result; the emitted gases then stream more or less radially outwards from the spot along the surface, producing the radial fibrous structure seen in photographs of the penumbra of spots. The vortical motion of the heated gas gives rise to intense magnetic fields, comparable in strength to the magnetic field between the pole-pieces of a fair-sized dynamo. Spots frequently occur in pairs and the magnetic fields associated with the two spots of a pair are of opposite polarity, like the two poles of a magnet. This is a consequence of the vortical motions around the two spots being in opposite directions.

Suppose the leading spot of a pair in the Sun's northern hemisphere has positive polarity; then we find that the leading spot of a pair in the southern hemisphere has negative polarity, the circulations around the leading spots in the two hemispheres being in opposite directions. We may compare with this the atmospheric circulation around cyclonic disturbances on the Earth, which is in the anti-clockwise direction in the northern hemisphere, and in the clockwise direction in the southern hemisphere. The leading spots in the two hemispheres keep their respective polarities for one complete sun-spot period, or, in other words, for about

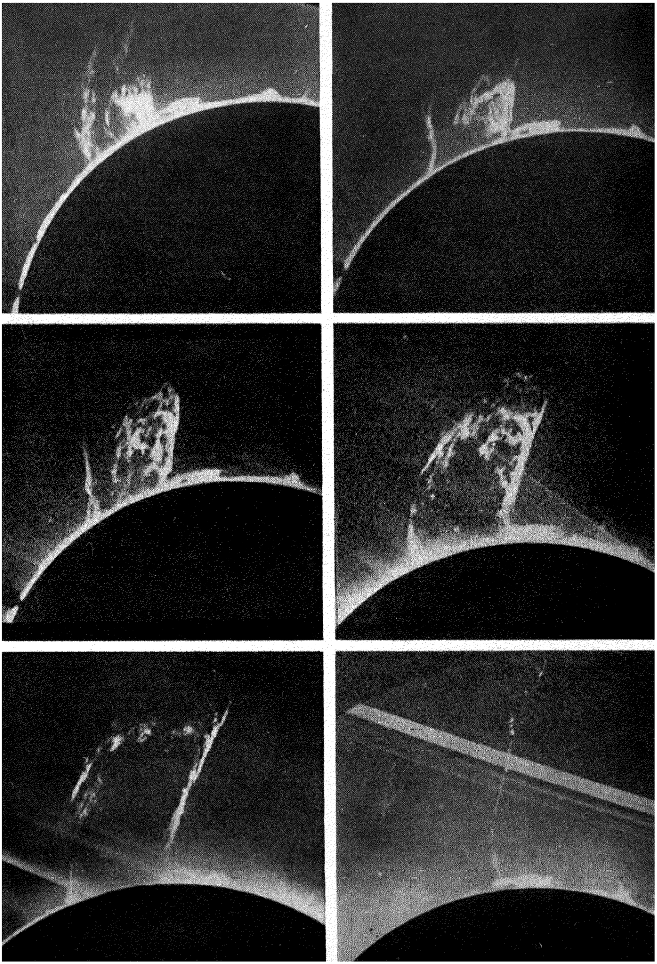


PLATE XVI.—PHOTOGRAPHS SHOWING SUCCESSIVE STAGES IN THE DISSIPATION OF A PROMINENCE ON MAY 26, 1916.

The interval of time from the first to the last photograph is 64 minutes. The top of the prominence rose 250,000 miles in half an hour.

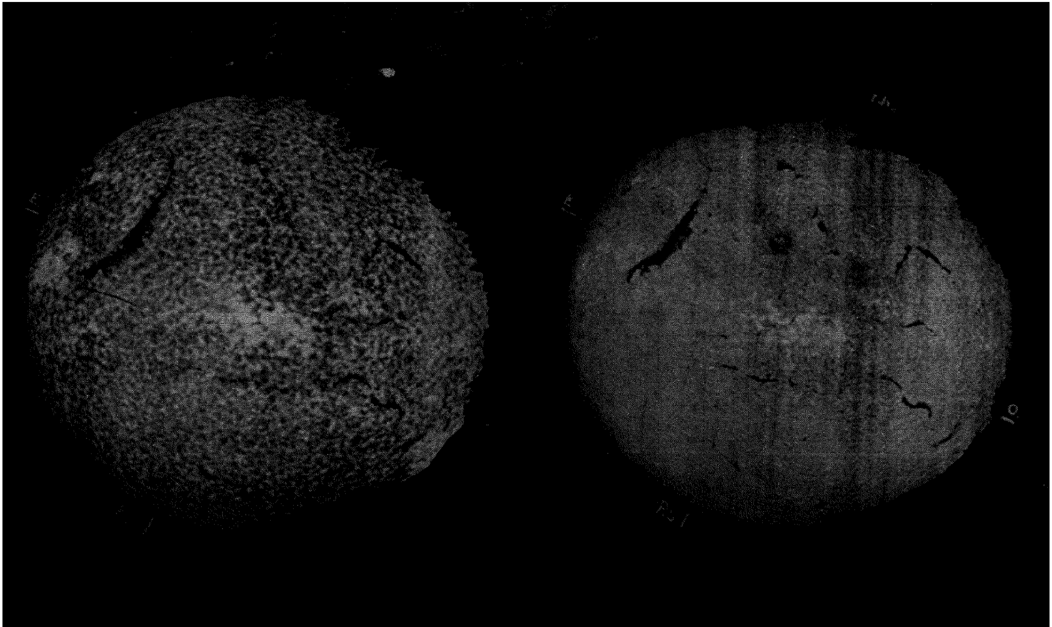


PLATE XVII.—THE SUN PHOTOGRAPHED IN THE LIGHT OF CALCIUM (LEFT) AND OF HYDROGEN (RIGHT).
The position of the Sun's axis of rotation is marked.

11 years; but when the next period commences, the leading spots in each hemisphere show the polarity opposite to that previously shown. We do not know what the real explanation of this regular reversal of the polarities of the spots may be, but it would seem to indicate that the fundamental period for the Sun is twice the normal 11-year sun-spot period.

When the face of the Sun is entirely hidden by the Moon passing in front of it at a total eclipse of the Sun, gigantic red tongues of flame are usually to be seen standing out from the Sun's limb to distances of many thousands of miles. These jets of flame are called "prominences." When a total eclipse of the Sun takes place, the period of totality, during which the Sun is completely hidden, is brief, never lasting for longer than about 7½ minutes, and the total phase is visible only from a very limited portion of the Earth's surface. Total eclipses are therefore rare occurrences in any given region of the Earth. There have been total eclipses visible from some part or other of the British Isles on the following dates since the beginning of the fifteenth century: 1424, June 26; 1433, June 17; 1598, March 6; 1652, April 8; 1715, May 2; 1724, May 22; and 1927, June 29. The next total eclipse visible in Great Britain will occur in 1999, August 11, and will be visible from near Land's End. It is therefore fortunate that by means of an instrument called a spectroheliograph it is possible to photograph the prominences at any time when the Sun is visible.

The prominences show an enormous variety of shapes and sizes and vary greatly in behaviour. They

may persist for many days or even weeks, without violent changes, some appearing as fountains of flame, others as pyramids of fire and others as vividly bright columns. Many prominences, on the contrary, show extremely rapid and violent changes, evidences of tremendous disturbances occurring at or beneath the surface of the Sun. At the total eclipse of the Sun on May 29, 1919, a great prominence was observed, appearing like a gigantic prehistoric mammoth, about 300,000 miles in length and about 20,000 miles in height. We shall briefly describe the history of this prominence, as a typical example of one of the larger prominences. It was first seen on March 22, more than two months before the eclipse; it was then already about 100,000 miles in length. During the following weeks it gradually grew in brightness, in length and in height. By May 27 it had grown very considerably, and it then appeared as an enormous body of interlacing streamers which were continually shifting. On May 29, at its southern end, there was a brilliant column which had a clawlike structure, as though it was attached to the Sun by roots. At the north end there was a more slender column reaching down to the Sun's surface, and in between there were faint streamers connecting the body of the prominence with the Sun. The prominence now began to show signs of rapid changes. The column at the north end broke away from the Sun's surface and the main body of the prominence started to rise rapidly. By 3 a.m. (G.M.T.) it had risen to a height of 140,000 miles and by 5.30 a.m. to 200,000 miles. The main body of the prominence had now become completely

detached from the Sun, leaving merely the stump with its claws rooted to the Sun's surface; it had a spiral structure as though coiled into a gigantic spring. When last seen, this enormous cloud of heated gas, about 250,000 miles in length, was at a height of more than 500,000 miles above the surface of the Sun and was rapidly receding from it, in the process of being blown away into outer space. It had risen 375,000 miles in about 5 hours. The two ends of the initial prominence remained visible until August 5.

When the eruptive stage of a prominence sets in, it is not uncommon for the prominence, or at least for the main portion of it, to be hurled upwards at the rate of tens of thousands, or even of hundreds of thousands, of miles per hour. In Plate XVI are reproduced some photographs showing the remarkably rapid changes observed in a prominence which appeared on May 16, 1916. In about one half-hour the top of this prominence rose by fully 250,000 miles.

By means of the spectroheliograph, sunlight of a single wave-length can be separated and the Sun can be photographed in light of that wave-length. This enables us to photograph the Sun in the light of hydrogen or calcium or some other element, such as iron. Such photographs give a representation of the distribution of the substance, by whose light the photograph was taken, over the Sun. In Plate XVII are shown photographs of the Sun taken on the same day in the light of calcium and of hydrogen. The photograph in calcium light shows a coarse mottled structure; the bright patches are

regions of intense radiation; the darker patches represent cooler clouds of calcium vapour, each cloud being much larger than the Earth. The photograph in hydrogen light shows much finer structure. A number of long dark markings are seen on both photographs, which will be found to correspond closely. These are prominences seen in projection on the Sun's disc; being much cooler than the main body of the Sun, a prominence appears dark when seen against the hotter and brighter disc. In Plate XVIII we see a prominence at first at the limb of the Sun; it is gradually carried round by the Sun as it rotates, and in the last photograph the prominence appears as a dark marking on the disc.

The number of prominences on the Sun fluctuates with the sun-spot cycle, the prominences being most numerous when sun-spots are most numerous and vice versa. The two photographs of the Sun, taken with calcium light, in Plate XIX illustrate the contrast between the quiescent state of the Sun at sun-spot minimum and its disturbed state at sun-spot maximum. The photograph taken at sun-spot minimum shows no spots and only a few small prominences. That taken at sun-spot maximum shows several groups of spots and many prominences.

We are now in a position to understand why there seems to be a connection between sun-spots and various happenings on our Earth, such as magnetic storms and auroræ. We have seen that matter can be ejected with great speeds from the Sun; this matter comprises atoms, many of which have had some of their electrons knocked off them and are therefore electrically charged, together with free electrons

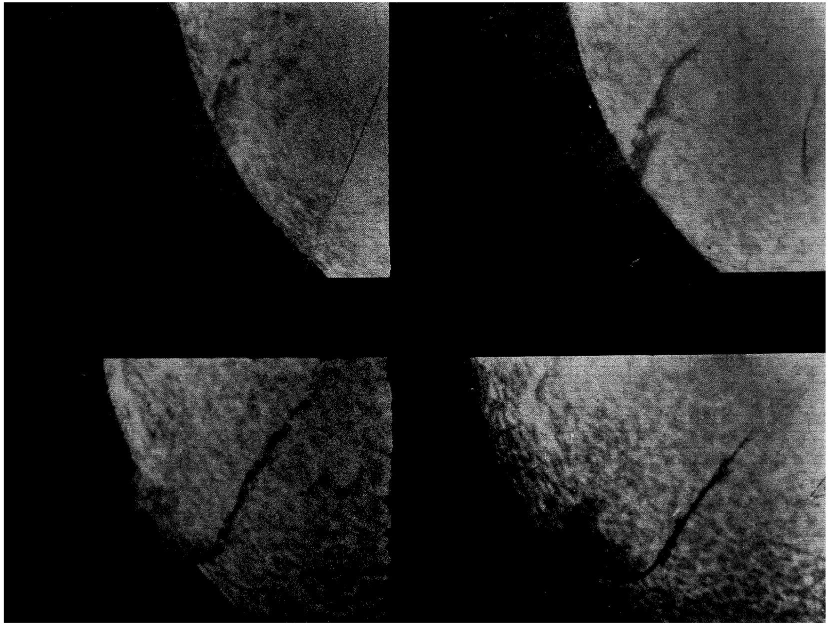


PLATE XVIII.—PROMINENCE, FIRST SEEN AT THE LIMB OF THE SUN, SHOWING ITS MOTION ON TO THE SUN'S DISC.

The photographs were taken on August 26, 27, 28, 29, 1929.

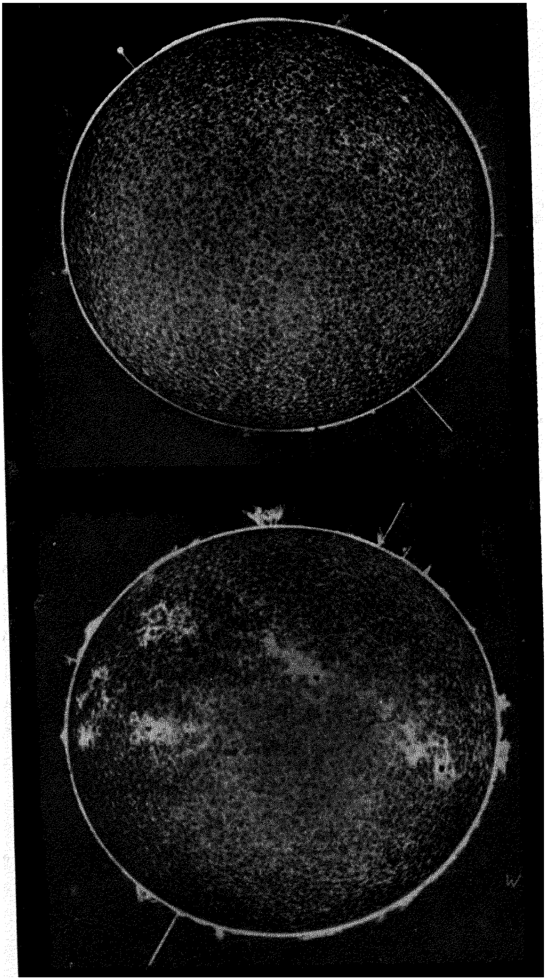


PLATE XIX.—THE SUN, PHOTOGRAPHED IN CALCIUM LIGHT, AT SUN-SPOT MINIMUM (ABOVE) AND AT SUN-SPOT MAXIMUM (BELOW).

There are no spots and few prominences in the upper photograph : in the lower there are several spots and many prominences. The position of the Sun's axis of rotation is shown in each photograph.

which carry a negative charge. From time to time streams of these electrically charged particles will approach near to the Earth; they are then influenced by the Earth's magnetic field, which causes them to move in a spiral motion towards the two magnetic poles. On entering our atmosphere, electrical effects are produced which give rise to displays of auroræ; these are most frequent and most vivid in the regions around the magnetic poles. The charged particles also ionize the upper layers of the atmosphere and make them a conductor for electricity; it is the magnetic effects produced by the electrical currents circulating in these ionized layers that we call magnetic storms. The ejection of charged particles from the Sun in the way we have described occurs most frequently near the time of sun-spot maximum, when sun-spots and prominences are most numerous. The general connection between sun-spot activity and the appearance of auroræ and magnetic storms is therefore accounted for.

It is possible to trace effects due to the sun-spot cycle in other directions. The facility with which radio waves can travel round the Earth depends upon the state of ionization in the ionosphere or ionized region of the atmosphere—the "radio roof of the world," as it has been called. This is so intimately connected with the frequency of appearance of sun-spots that it is not surprising that the ease with which distant radio stations can be detected is closely related to the sun-spot cycle. A more obscure phenomenon is the relationship between sun-spots and weather. That there is a connection is undoubted, but the weather is such a complicated

phenomenon that the dependance upon sun-spots is usually smothered by a host of other factors. It is curious that the connection is most clearly shown in the rings of trees. If a cross-section of the trunk of a tree is examined, it will be noticed that the annual rings are not uniformly spaced. The consecutive rings in a group may be crowded close to one another; but those in an adjacent group may be comparatively wide apart. Each ring marks the growth of the tree in the course of a year, the growth depending upon a variety of factors—such as the amount of rainfall and its distribution during the year, the temperature changes and the amount of sunshine throughout the year. Some factors are more important than others, and the relative importance of the several factors varies from one region to another. The tree ring gives an integrated effect of these factors acting throughout the whole year. Dr. Douglass has found that in the arid regions of Arizona and New Mexico the rings show a clear dependance upon sun-spots, the width being greatest when sun-spots are most numerous. He succeeded in tracing the eleven-year sun-spot cycle in the Arizona pine trees for a period of 500 years, with the exception of an interval from 1650 to 1725, when the evidence of the sun-spot effect vanished. Some years later Dr. Douglass heard from Mr. Maunder, who was in charge of the solar department of the Greenwich Observatory, that he had found that there were practically no sun-spots between 1645 and 1715—unexpected confirmation of the results derived from the study of the rings. By using the evidence afforded by the tree rings, Dr. Douglass

has succeeded in fixing the date of the ruins of Pueblo Bonito, the oldest and largest of the great Indian communities in Chaco Canyon, New Mexico, which had for long proved a stumbling-block to archæologists.

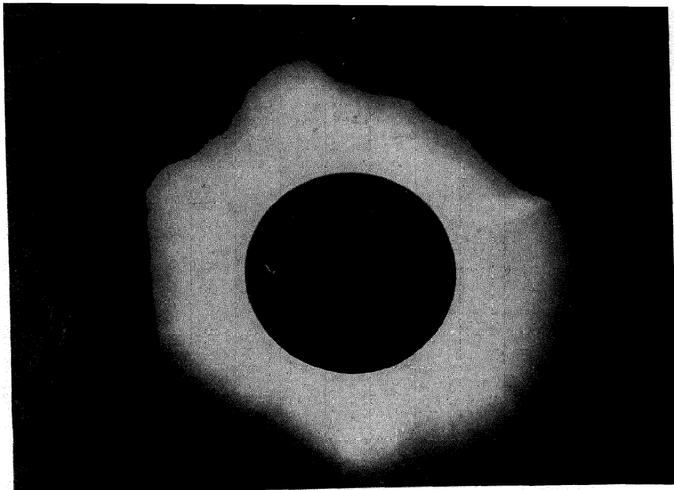
At the time of a total solar eclipse, as the last thin crescent of the Sun is hidden by the Moon, a bright *aureole* surrounding the Sun flashes out. This is called the corona. It has about one-half the brightness of the Full Moon or about one-millionth of the brightness of the Sun. The light of the corona is thus so much weaker than sunlight that it is not surprising that we can see the corona only at the time of a total eclipse of the Sun. The inner portion of the corona has a slightly yellowish tinge; the outer portion is of a pearly white colour. The brightness falls off very rapidly with distance from the limb of the Sun. The corona can usually be traced to a distance of two or three diameters from the Sun. It thus appears that the Sun is surrounded up to a distance of a couple of million miles by a very tenuous atmosphere. The light of the corona appears to be mainly sunlight which is scattered by this atmosphere.

The general shape of the corona varies during the sun-spot cycle in a very marked way. When sun-spots are most numerous the corona is fairly compact, without very long streamers, and is distributed more or less uniformly around the Sun's disc. At sun-spot minimum, long curved streamers stretch out from the equatorial zones, whilst around each pole of the Sun's axis is a tuft consisting of a large number of short streamers, suggesting the lines of

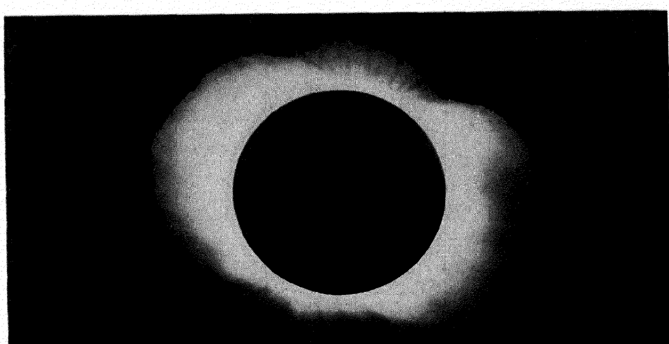
force near the two poles of a bar magnet (see Plate XX). At other times the shape of the corona is intermediate between the two extremes. We do not know the explanation of these changes of shape, which recur with such regularity that we can predict with considerable accuracy the shape of the corona to be expected at a future eclipse.

The structure of the inner corona is very complicated, showing numerous filaments and curved arches, particularly in the neighbourhood of spots or prominences.

The Sun is continuously pouring out a dense stream of radiation in the form of light and heat; its surface is therefore intensely bright and extremely hot. Langley performed an experiment to compare the brightness of the Sun's surface with the brightness of molten steel. Fifteen tons of molten iron were placed in a converter; half a ton of silicon and carbon was then added and air was blown through the glowing mass to raise its temperature. A further 15 tons of molten iron were poured into the converter, appearing, as Langley said, like chocolate poured into a white cup. After thorough mixing, the cataract of liquid steel was discharged, scattering showers of brilliant scintillations all around. With special instruments Langley made measurements of the brightness of the cataract of fire, which was so bright that dark glasses were needed to protect the eyes. He found that, so far as the light-rays which affect the eye are concerned, the surface of the Sun was five thousand times brighter per square foot than the molten steel, and taking all the radiations—light and heat together—



(*a*) SOLAR CORONA, May 9, 1929 (NEAR SUN-SPOT MAXIMUM).



(*b*) SOLAR CORONA, May 28, 1900 (NEAR SUN-SPOT MINIMUM).

PLATE XX.

the radiation from the Sun was 87 times more intense than that from the molten metal.

What do we mean when we speak of the temperature of the Sun? The Sun has no solid boundary but is entirely gaseous. If we were able to travel into its interior, we should find the temperature rapidly mounting up: it would measure at first several thousands of degrees, then tens and hundreds of thousands, and finally, when we were well on the way into the interior, millions of degrees. The radiation which we receive from the Sun is a mixture of radiations which originated at different depths in the Sun and therefore at different temperatures. It would seem, then, that we are not justified in using the term "the temperature of the Sun."

Suppose we conceive a solid body, the size of the Sun, made of a material which will not melt or vaporise and imagine it to be gradually heated uniformly. As it is heated it will after a time begin to glow with a dull red heat, then it will become successively red hot, yellow hot, white hot and so on. At a certain stage in this heating process the body will be giving out the same amount of light and heat as the Sun. We should find that, when this is so, the colour is the same yellow colour as the Sun. The "effective temperature" of the Sun is the temperature of the hot body when it has the same colour as the Sun and the same output of heat and light. When we speak of the temperature of the Sun, we must use the term in this sense.

The effective temperature of the Sun, defined in this way, is about 6,000° C. This is much higher than the melting-point of carbon. We can gain a better

appreciation of what such a temperature implies by stating that every square foot of the Sun's surface is radiating energy at a rate of a 9,000-h.p. engine or every square inch at the rate of a 62-h.p. engine. The proportion of this radiation which the Earth receives is only one part in 2,200 millions. Yet the energy received by the Earth in the form of solar radiation amounts to nearly 5,000,000 h.p. per square mile of surface. If we were able to utilise all of this energy and valued it at the rate of $\frac{1}{4}$d. per Board of Trade unit, the monetary value of the solar energy striking the Earth every second would be about £200,000,000. In comparison with the enormous potential value of the energy which the Earth is receiving, our National Debt seems a mere trifle; if only we could convert the Sun's energy into cash, we could pay it off within one minute. Various mechanisms for utilising some of the Sun's energy have been proposed, but none has yet been successful on a commercial scale. Probably in the years to come, when our supplies of coal and of oil will have been exhausted, some means by which a portion of this energy can be captured and harnessed into the service of man will be discovered.

For how long the Sun has been radiating energy at this rate we do not know. The evidence of geology points to considerable changes of climate on our Earth during geological time—alternations of ice-ages and warm periods. The only way in which it seems possible to account for such variations is on the supposition that there have been fluctuations in the output of the Sun's radiation. Yet, on the other hand, it does not seem possible that the variations can

have been considerable—at least since the time when man appeared upon the Earth. If the stellar magnitude of the Sun were changed in either direction by half a magnitude—not a large variation for a variable star—conditions on the Earth would be such that human life would become impossible.

From various considerations it seems probable that the Sun's output of radiation has not differed greatly from its present value throughout the life history of the Earth; in other words, for several thousand million years. How does the Sun maintain so great an output for so long a time? If the energy were derived solely from the store of heat within the Sun, the radiation could only continue for a few thousand years at most. Lord Kelvin supposed that the Sun was gradually shrinking, the matter of which it is composed slowly falling towards its centre. A decrease in the radius of the Sun of about 75 yards in the course of a year would release enough energy to maintain the Sun's radiation; such a slow decrease in the radius could not be detected by observation. But on this theory the Sun's energy would all have been expended in a mere 25 million years or so. Even if we take into account the energy that can be provided by the disintegration of the radioactive bodies, such as uranium or radium, and suppose that the Sun was originally composed entirely of uranium, we can add only a few million years to the possible lifetime of the Sun, as a giver of heat and light. We must look for some other explanation, and we shall return to this question again when we come to consider the ages of the stars (Chapter XII).

Chapter VII

GIANT AND DWARF STARS

When we look at the sky on a clear moonless night we cannot see more than some 2,000 or 2,500 stars. In the whole of the heavens the number of stars visible to the average eye is between six and seven thousand, but at any one place and time one-half of these are below the horizon and near the horizon the fainter ones cease to be visible. It is therefore somewhat surprising that from time immemorial the number of stars in the sky has been used, equally with the number of grains of sand on the seashore, to denote a number inconceivably large. "As the host of heaven cannot be numbered, neither the sand of the sea measured" (Jeremiah). But even a small telescope reveals an enormous increase in the number of stars; with a 3-inch telescope it is possible to observe about one million stars, and every increase in telescopic power brings more stars into view.

The stars were divided by the ancients into constellations, as a convenient method of describing the position of any star and identifying it. The names of many of the constellations, particularly those of the zodiac—the zone of the sky bordering the path of the Sun in the heavens—are of very great antiquity. The origin of these names is not known with certainty, but it is believed that they originated in Mesopotamia, for the animals are those of the Bible. There is no constellation named after the tiger, the

elephant, the hippopotamus or the crocodile; it is therefore unlikely that the names originated in either India or Egypt. Many other names have been drawn from Greek and Roman mythology, whilst the names of about forty constellations have been given since 1600, to include stars which did not belong to any of the older constellations.

The stars were originally described by their positions in the constellations; thus, for instance, reference was made to the star at the end of the tail of the Little Bear or to the star at the tip of the right horn of the Bull. In 1603 Bayer, when publishing his *Uranometria*, containing a series of star maps with descriptions, adopted the plan which has since been followed of denoting the stars in a constellation by the letters of the Greek alphabet, usually, but not always, assigned in order of brightness. Some sixty or so of the brighter stars have proper names, of Greek, Latin or Arabic origin, in common use. Thus Sirius, the brightest star in Canis Major, is Alpha Canis Majoris; Betelgeuse, the brightest star in Orion, is Alpha Orionis. Other very bright stars, such as Alpha Centauri, have never been given proper names.

Other stars are named by the numbers assigned by Flamsteed, the first Astronomer Royal, together with the name of the constellation, for example, 61 Cygni; or by the number of the star in the earliest star catalogue in which it is to be found, e.g. Lalande 21185 is the star of this number in the catalogue of Lalande (1790). Names such as this may appear very prosaic, but they achieve their purpose of identifying the stars.

Whether we look at the stars with the naked eye or with a telescope, we notice that some appear much brighter than others. "One star differeth from another in glory." Hipparchus, who lived in the second century before Christ, graded the stars visible to the naked eye into six classes according to their brightness. The brightest stars he placed in class 1, the faintest in class 6. A star in class 1 is called a first magnitude star; a star in class 6 is called a sixth magnitude star. To the eye, the difference in brightness between, say, a first magnitude and a second magnitude star appears equal to the difference in brightness between a second magnitude and a third magnitude star or between a fifth magnitude and a sixth magnitude star. But owing to psychological factors connected with vision, the true differences in brightness—measured by comparing the energy received in the form of light from the stars—are far from equal. If we take the brightness of a star of the sixth magnitude as unity, the relative brightness of stars of other magnitudes is as follows:—

Magnitude . .	6	5	4	3	2	1
Brightness . .	1	$2\frac{1}{2}$	$6\frac{1}{4}$	16	40	100

We see that the difference in brightness between the fifth and sixth magnitudes is $1\frac{1}{2}$ units; but between the second and first magnitudes it is 60 units. It will be noticed that a difference of one magnitude corresponds to a ratio of brightness of about $2\frac{1}{2}$, and a difference of five magnitudes to a ratio of exactly 100.

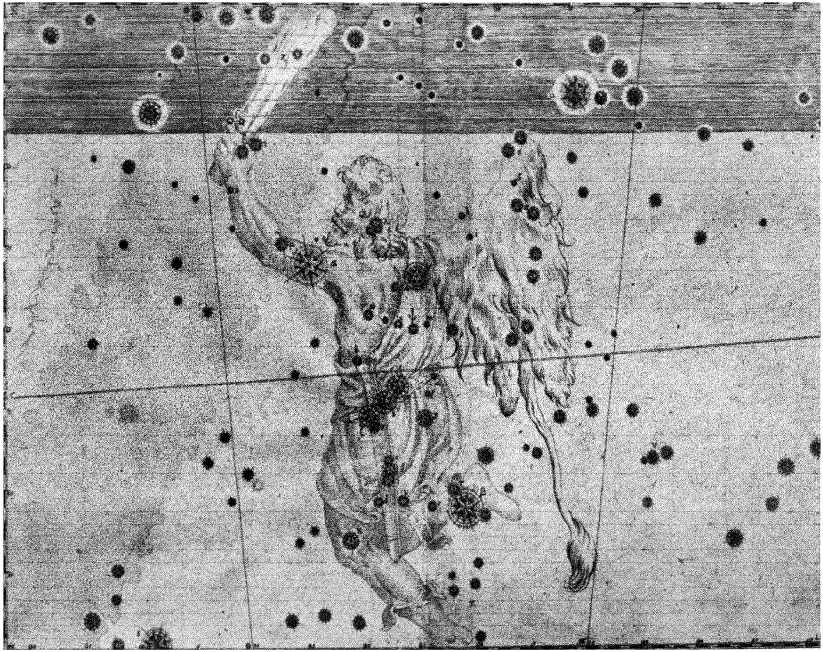


FIG. 5.—The Constellation of Orion as depicted in Bayer's *Uranometria* 1603.

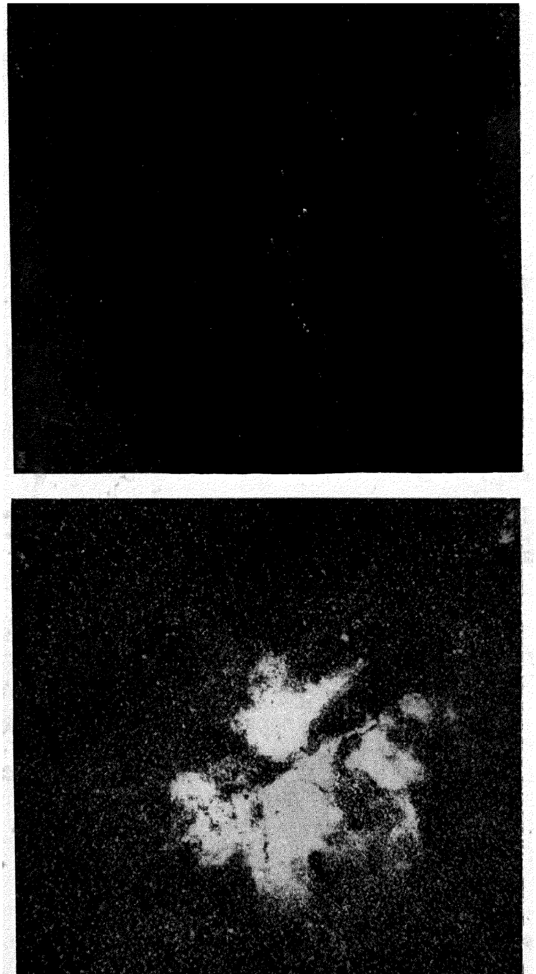


Plate XXI.—Portion of the Constellation of Carina.

The upper photograph has an exposure of 1 hour, the lower of 24 hours.

The long exposure reveals extensive faint nebulosity, not seen in the short-exposure photograph.

After the invention of the telescope, when fainter stars began to be observed, the same system of classification was extended to these stars. Gradually the system was made more precise and the magnitude classes were subdivided, so that the magnitude as now used provides an exact indication of the apparent brightness of the star. For the very bright stars, the magnitudes are denoted by 0, or −1 or intermediate values. Thus Alpha Tauri (Aldebaran) has magnitude 1·0; Alpha Centauri has magnitude 0·0 and Sirius (the brightest star in the sky) has magnitude −1·6. A negative magnitude appears incongruous, even though logical. What these figures imply is that Alpha Centauri is 2½ times and Sirius 11 times as bright as Aldebaran. On the same system, the stellar magnitude of the Sun is −26·7 and of the Full Moon is −12·6. Expressed in units of brightness we may write:—

Brightness of	Sun	120,000,000,000
,,	Moon	275,000
,,	first magnitude star	1
,,	sixth magnitude star	·01
,,	eleventh magnitude star	·0001
,,	sixteenth magnitude star	·000001
,,	twenty-first magnitude star	·00000001

The above figures refer to the apparent brightness as seen by us and have no relationship to the true brightness or intrinsic candle-power.

It is of interest to compare the numbers of stars in the whole sky brighter than certain limits of magnitude. The following figures are based on counts of stars and are necessarily rather uncertain for the fainter magnitudes.

Magnitude Limit.	No. of stars.	Magnitude Limit.	No. of stars.
2	41	12	2,270,000
3	138	13	5,700,000
4	530	14	13,800,000
5	1,620	15	32,000,000
6	4,850	16	71,000,000
7	14,300	17	150,000,000
8	41,000	18	296,000,000
9	117,000	19	560,000,000
10	324,000	20	1,000,000,000
11	870,000		

As the limiting apparent brightness is decreased, there is a rapid increase in the number of stars. This is illustrated by the two photographs of a part of the constellation of Carina in Plate XXI. These were taken with the same telescope, but with exposures of 1 hour and 24 hours respectively. Fainter stars are photographed with the longer exposure and many more stars are therefore shown.

The total light from all the stars is equal of the light of 1,440 stars of the first magnitude. It follows that the Full Moon gives about 200 times as much light as all the stars together.

The relative brightness of the stars as they appear to the naked eye does not give any information about their true relative brightness. The apparent brightness of a star depends upon two factors—its intrinsic brightness or candle-power and its distance. If it were true, as the Greek philosophers supposed, that the stars were all fixed to a sphere, they would all be at the same distance and the apparent brightness would then give a measure of the true or intrinsic brightness. But the stars are not all at the same distance; we cannot therefore learn anything about their true luminosities or candle-powers until their

distances have been determined. A single candle at a distance of 100 yards would appear of the same brightness as four candles at a distance of 200 yards or nine candles at a distance of 300 yards and so on. If the same star were moved towards us to one-tenth of its previous distance it would appear 100 times brighter; if it appeared at first as of magnitude 6, it would now appear of magnitude 1.

The first astronomer to arrive at conclusions as to the distances of the stars which are anywhere near correct was Sir Isaac Newton. He argued that, as the stars do not move in orbits round the Sun, like the planets and comets, they must be so far away that they are not affected by the gravitational pull of the Sun. They must be, at the very least, many hundreds of times as far away as Saturn. The stars must therefore be self-luminous bodies like the Sun or we should not be able to see them. He suggested that they are probably comparable with the Sun in brightness. He estimated that the Sun would have to be moved to about 100,000 times its distance if it were to appear like Sirius, the brightest star. If, then, Sirius is comparable to the Sun in candle-power, it must be at a distance of about 10 million million miles. This is actually an underestimate of the distance of Sirius, but the order of magnitude is correct.

The method used to determine the distances of the nearer stars is exactly analogous to the method used by a surveyor to determine the distance of a distant object, S (Fig. 6), on the Earth. The surveyor first carefully measures off a suitable base-line AB. He places his theodolite at A and measures the angle

SAB and then moves his theodolite to B and measures the angle SBA. If the line AB is drawn to scale and the lines AS, BS are drawn so that the angles SAB, SBA are equal to the measured angles, the lines intersect in S and by measuring SA and SB the distance of S from A or B can be found; the more accurate method used by the surveyor is to calculate the distances by means of trigonometry.

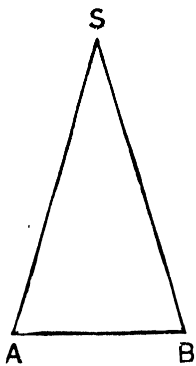


FIG. 6.—Measurement of distance by triangulation.

The astronomer proceeds in essentially the same way when he determines the distance of a celestial object. If he wishes to measure the distance of the Moon or of a planet, observations can be made from two observatories, well separated in distance, such as Greenwich and the Cape. The length of the base-line joining these two observatories can be computed from the data as to the shape and size of the Earth which have been derived from surveying operations. The measurement of the distance of any one member of the solar system is sufficient to fix the distances of all the other members, because the whole system can be plotted to scale without the measurement of a single distance; the measurement of any one distance enables the scale of this plot to be determined.

For the distances of the stars the same method is again employed, but on account of the great distances of the stars it is necessary to use the longest

possible base-line. The longest base-line available is the diameter of the orbit of the Earth around the Sun, which is about 186,000,000 miles. To illustrate the method, suppose S_1, S_2 in Fig. 7 are two stars in a line with the Sun, S, and that observations are made when the Earth is at A and then, six months later, when it has reached the opposite end of its orbit at B. The near star S_1 will appear first to one side of the more distant star S_2 and then to the other side. As the Earth moves round its orbit, S_1 will appear to swing backwards and forwards with respect to S_2.

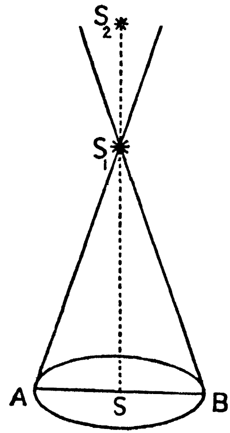


FIG. 7.—Method of determining stellar distances.

When Copernicus put forward his theory that the Earth moves round the Sun, it was objected by his opponents that, if the theory were true, relative shifts of the positions of the near and distant stars, such as we have just described, should be seen. They argued that since such shifts were not observed, the theory of Copernicus could not be correct.

The explanation is that the distances of even the nearest stars are so great in comparison with the diameter of the Earth's orbit that the shifts are extremely small and can only be detected by the most refined observations. The nearest star is so far away that if we were to attempt to draw the triangle AS_1B to scale and represented the distance

AS of the Sun from the Earth (93,000,000 miles) by 1 inch, we should need a strip of paper more than four miles long! Imagine a surveyor attempting to measure the distance of an object four miles away by making observations from the ends of a base-line only 2 inches in length. It is not surprising that repeated attempts to determine the distances of the stars failed. It was not until 1835 that the first stellar distances were determined and then three different astronomers, working independently and using methods which—though in principle the same—were different in detail, each succeeded in measuring the distance of a star.

The nearest known star is about 25 million million miles distant. Such a great distance does not convey very much to the mind because the unit in which it is expressed is too small in comparison with the distance itself. We need a unit which is more comparable with the distance. If I say that the distance from London to Edinburgh is 25 million inches, I do not convey a very clear idea of how far apart these two cities are. In dealing with stellar distances it is more convenient to express them in terms of the time which light takes to travel to us from the star, just as we might express a distance on the Earth as so many hours' walk or so many hours by train. Light travels 186,000 miles in a second and so could girdle the Earth several times in a single second. Using this method of expressing distances, we can say that the distance of the Moon is about 1¼ light-seconds, the distance of the Sun is 8 light-minutes and the distance of Pluto is about 5½ light-hours. This mode of expressing the distance

of a celestial body has the advantage of reminding us that we never see the particular body where it actually is. We do not see the Sun in its true position but in the position it occupied eight minutes previously, when the light by which we see it set out on its journey towards the Earth.

Expressed in light-time, the nearest star (Alpha Centauri) is at a distance of about four light-years, the light-year being approximately 6 million million miles. We see this particular star where it was about four years previously; it is actually somewhere about 200 million miles away from the position in which we see it.

By such means we can determine with reasonably good accuracy the distances of the nearer stars, up to distances of about 500 light-years. For greater distances, the results become rather uncertain; our base-line, although 186,000,000 miles in length, has become hopelessly inadequate. The measurement of a distance of 500 light-years, by making observations at the two ends of this base-line, is equivalent to the measurement of the distance of an object 3,000 miles away by making observations from two points 1 foot apart. The exploration of space to greater distances must be based upon indirect methods, which we shall refer to later. In the meantime, it is well to recall the steps that are necessary to measure how far away are the nearer stars. We start with the surveyor who measures a base-line on the Earth with an accurate inch-tape; from this measured base-line he proceeds by geodetic triangulation to determine the shape and size of the Earth. From two stations on the Earth's sur-

face the astronomer observes one of the planets, and determines its distance from the Sun and is able to infer the distance of the Earth from the Sun. Having found the size of the Earth's orbit, he makes observations of the stars from opposite ends of the orbit and so derives their distances.

When the distances of the stars have been determined we can allow for the differences in distance and compare their true brightness or total candle-power with the brightness or candle-power of the Sun.

The total candle-power of a star being known, we can learn something about its size, provided we know the colour or, what is really equivalent, the temperature of the star. Some stars are yellow like the Sun; others are red, orange, white or blue. The red stars are comparatively cool, the blue stars are very hot. To each colour there corresponds a definite temperature. We have seen that the temperature of the Sun is 6000° C.; a red star has a lower temperature of about 3000° C., whilst a blue star may have a temperature of 15,000° C. to 30,000° C. By means of an accurate measurement of the colour of the star, we can therefore conclude that the star is red-hot, or yellow-hot, or white-hot, and we can estimate the candle-power of each square foot of its surface. Combining this information with our knowledge of the total candle-power of the star, we can deduce the total area of its surface and therefore its size.

We shall look first at the brightest naked-eye stars and then at the stars nearest to the Sun and see to what extent they differ from the Sun as regards both

true brightness and size. The table gives the names of the twelve brightest stars in the first column, and the stellar magnitudes in the second column. The distances in light-years are contained in the third column. The candle-powers of these stars, in terms of the candle-power of the Sun as a unit, are given in the fourth column. The last column gives the radius of each star in terms of the radius of the Sun as a unit. Some of these stars are twin stars; in such cases the data refer to the brighter of the components.

Name.	Stellar Magnitude.	Distance in light-years.	Candle-power (Sun = 1).	Radius (Sun = 1).
Sirius	− 1·6	9	26	2
Canopus	− 0·9	650	80,000	180
Vega	+ 0·1	26	50	2
Capella	0·2	47	150	12
Arcturus	0·2	41	100	30
Alpha Centauri	0·3	4	1	1
Rigel	0·3	540	18,000	38
Procyon	0·5	10	5	2
Achernar	0·6	66	200	4
Beta Centauri	0·9	300	3,100	11
Altair	0·9	16	9	1
Betelgeuse	0·9	190	1,200	290

This table shows several features of interest. In the first place we notice that the dozen brightest stars include stars which are near and stars which are fairly distant. The nearest known star, Alpha Centauri, is one of the twelve. Sirius, the brightest star in the sky, is relatively near to us; but Canopus, the second brightest star, is the most distant of this group. The fourth column shows that there is a

wide range in candle-power of the stars. Alpha Centauri is comparable with the Sun, but Canopus is a much more brilliant object. It is about 80,000 times as bright as the Sun. If Canopus were as near as Alpha Centauri it would be a magnificent object in the sky, for it would appear nearly half as bright as the Full Moon and would cast shadows on

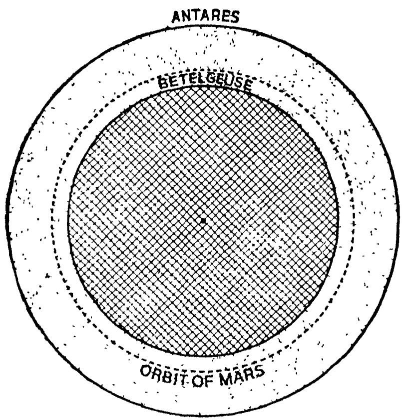


FIG. 8.—Relative size of Antares, Betelgeuse and the Sun. (The Sun is the small black dot at the centre.)

the Earth. Rigel is another star in this group which has high candle-power.

The last column gives a comparison of the sizes of the stars, and a wide range in size will be noticed. Several of the stars, such as Vega, Alpha Centauri, Procyon, Achernar and Altair, are not very different from the Sun in size; it may be remarked that this group of the brightest naked-eye stars does not contain any which are smaller than the Sun. But two

of the twelve stars, Betelgeuse and Canopus, are giants compared with the Sun. Betelgeuse, for instance, is so large that it could contain 24 million bodies of the size of the Sun.

We see, therefore, that stars vary greatly both in actual dimensions and in candle-power. The stars which appear to us as the brightest stars in the sky may be either near and of moderate candle-power, or distant and of high candle-power. We may expect that any stars which are of candle-power much inferior to the Sun, even though fairly near to us, will not appear amongst the brightest stars in the sky.

It is of interest to examine next the nearest known stars and to compare them with the Sun both as regards size and candle-power. The data are given in the following table, which is arranged similarly to the preceding table. Both components of twin systems are given.

Name.	Stellar Magnitude.	Distance in light-years.	Candle-power (Sun = 1).	Radius (Sun = 1).
Proxima Centauri	10·5	4·2	0·0001	0·05
Alpha Centauri A	0·3	4·3	1·2	1·0
,, ,, B	1·7	4·3	0·3	1·2
Barnard's star	9·7	6·0	0·0004	0·11
Wolf 359	13·5	8·0	0·00002	0·025
Lalande 21185	7·6	8·3	0·005	0·38
Sirius A	− 1·6	8·6	26·0	1·8
,, B	8·4	8·6	0·0026	0·032
Innes's Star	9·5	9·6	0·0001	0·06
Procyon A	0·5	10·4	5·6	1·9
,, B	13·0	10·4	0·00006	0·004
Epsilon Eridani	3·8	10·7	0·28	0·8

We may note first the comparative emptiness of space. Within a distance of 10 light-years from the

Sun, we know of only seven stars (counting twin systems as single stars). If we take an average star and represent it by a tennis ball, a sphere of 10 light-years radius is about equal in size, on the same scale, to our Earth. If we imagine our Earth, therefore, as a hollow globe 8,000 miles in diameter, containing some half-dozen or so tennis balls, we have a fairly accurate picture of how empty space in the near neighbourhood of the Sun actually is.

This group of the nearest known stars includes the brightest star in the sky, Sirius, and three other bright naked-eye stars, Alpha Centauri, Procyon and Epsilon Eridani. But some of the stars have very low apparent brightness; the apparent brightness of Wolf 359 is only one-millionth that of Sirius. When we look at the column headed candle-power we see that the majority of the nearest stars have a very much lower candle-power than the Sun; Wolf 359 has only 1/50,000th of the candle-power of the Sun. As might be expected, the stars of very low candle-power are also small in size; three stars in the above list—the companions of Procyon and Sirius and Wolf 359—are actually only of planetary dimensions, being smaller than Neptune. The companion of Procyon is comparable in size with the small planet Mercury. We might be inclined to think that the companions of Procyon and Sirius should be regarded as planets moving round their parent Suns, rather than as Suns. We shall see later that this view is not tenable.

We have already compared Betelgeuse with the Sun. It is interesting to have the corresponding comparison between the Sun and the companion

of Procyon. The latter is so small that the Sun could contain 15 million bodies equal to it in size.

From this examination of two groups of stars, the brightest naked-eye stars and the nearest stars, we have learnt that there is a very wide range in the candle-power of the stars. If we represent the Sun

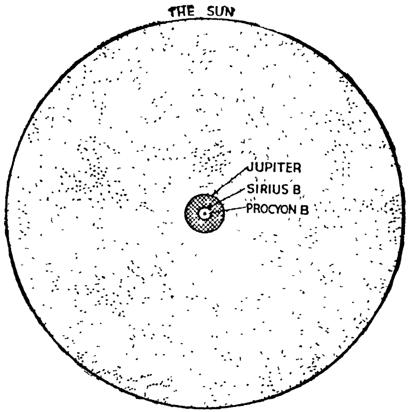


FIG. 9.—Relative sizes of the Sun, Jupiter, Sirius B and Procyon B. (Procyon B is the small black dot at the centre.)

by a single candle there are some stars which can be compared to a powerful lighthouse lantern and others which can be compared to a will-o'-the-wisp; the range in candle-power from one extreme to the other is of the order of one thousand million to one. The disparity in size, though not so great, is considerable. If we draw the circles to scale to represent the sizes of the various stars and make the companion of Procyon one inch in diameter, the Sun would have

a diameter of about 7 yards and Betelgeuse would have a diameter greater than one mile.

The stars which are large in size and of very high candle-power are called "giants." Those which are small in size and of low candle-power are called "dwarfs." There is no clear line of separation between the two classes, except for the red stars. When we examine these stars we find that they fall into two distinct groups; the stars in the one group are large and of high candle-power, those in the other group are small and of low candle-power. The orange stars can be fairly well divided in the same way, but for the yellow and white stars the two groups merge into one another. The Sun is to be regarded as a dwarf star, being a member of the fainter group of yellow stars.

The smallness of the companions of Sirius and Procyon suggested that they might be planets rather than stars. We have hitherto said nothing about the masses of the stars; we have seen, however, that the planets belonging to our Sun are all much less massive than the Sun itself. The mass of the Sun is about 20,000 times that of Neptune, with which we compared the small dwarf stars. If we can find a method by which we can weigh the companions of Sirius and Procyon we may hope to be able to decide whether they are planets or stars.

We have no hope of ever gaining any information about the weights of the great majority of the stars. The only means we have of finding how much matter a star contains is to measure its gravitational pull on another star; we really weigh the star. In everyday life we find how much matter any object

contains by measuring the gravitational pull of the Earth on it. In the case of a star alone in space, millions of millions of miles from its nearest neighbour, we cannot possibly detect any gravitational influence. But many stars are twin systems, con-

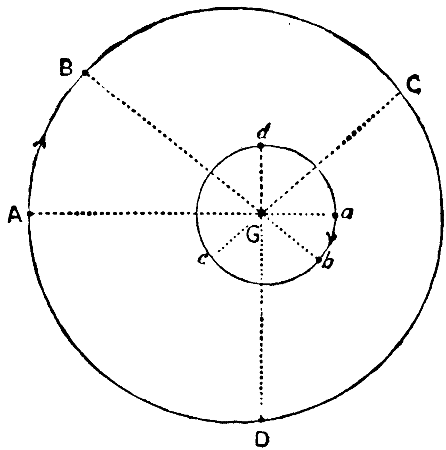


FIG. 10.—Relative orbits of stars in a twin system, showing corresponding positions.

sisting of two stars relatively close together, the one held fast in the gravitational pull of the other. The two stars must revolve round each other; if they ceased to do so, gravitation would draw them together and they would collide with one another. An example of such a twin system is the star Krüger 60; photographs of this system in the years 1908, 1915 and 1920 are reproduced in Plate XXII. A complete revolution of the one star about the other is completed in 44 years. When we make careful

observations of a system such as this we find that each star is moving around some point between the two stars. In Fig. 10, ABCD represents the orbit of one star, *abcd* that of the other star, A, *a* etc. being corresponding positions at the same instant. The stars move so that the line joining them always passes through the point G. The star which has the smaller orbit will be the more massive; the gravitational pull of the heavier star on the lighter star is exactly equal to the pull of the lighter star on the heavier, but equal pulls will disturb the lighter star more than the heavier. In the same way, the Earth pulls a stone with a force equal to that with which the stone pulls the Earth. But the stone is so much less massive than the Earth that it is the stone which falls towards the Earth. In Fig. 10, if AG is three times G*a*, the star at *a* which describes the small orbit has three times the mass of the star at A which describes the large orbit.

It is therefore possible in the case of a twin system to find the ratio of the weights of the two stars by comparing the sizes of their two orbits. If we now measure the distance of the system, we know the actual size in miles of the orbit of each star. We are then able to compare the weight of each of the stars with the weight of the Sun. The reason is that for any particular size of orbit, the period of one revolution is determined by the weights; the heavier the stars, the faster they must move if the orbit is to remain of the same size.

The outcome of investigations such as these is that we find that most stars contain about the same quantity of matter. It is very exceptional in a twin

system to find that one of the stars weighs more than three times the other or to find that the weight of either of them differs greatly from the weight of the Sun. A large majority of the stars have weights which lie between one-quarter and ten times the weight of the Sun. There are a few stars known which are exceptionally heavy; Plaskett's star is a twin system with two stars which do not differ greatly in weight, but their combined weight is more than 160 times greater than the weight of the Sun.

The comparatively small range in weight amongst the stars is a matter for surprise when we recall how widely stars differ from one another both in size and candle-power. Still more surprising is the comparison between the two components of some of the twin systems. We recall that the brightest star in the sky, Sirius, has a faint companion (called Sirius B in the table on p. 143) which sends out only one ten-thousandth part as much light as Sirius; the fainter star is so much smaller than the brighter that the larger star could contain about 180,000 stars of the size of the smaller. The weights of these two stars are not very unequal. The faint star has about the same weight as the Sun; the bright star has a weight $2\frac{1}{2}$ times as great. Procyon provides an even more striking contrast; the companion to Procyon is an extremely faint star which can be seen only with difficulty under the most favourable circumstances with powerful telescopes. It is only one-hundred-thousandth as bright as Procyon. The size of the faint star is not known with very great accuracy, but it is certainly so small that many millions of stars of the same size could be contained in

Procyon itself, although Procyon is not much larger than the Sun. The weight of Procyon is about $1\frac{1}{4}$ times that of the Sun; the weight of the companion is about two-fifths of the Sun's weight.

The faint companions of Sirius and Procyon are thus comparable to the planets in size, but comparable to the Sun in mass. For the amount of matter in them to be packed into so limited a space, they must have extremely high mean densities. We recall that the mean density of the Sun is rather less than $1\frac{1}{2}$ times the density of water; the companion of Sirius is on the average about 50,000 times denser than water. The companion of Procyon is a still more strange star. A match-box full of the material of which the companion of Sirius is composed would weigh a couple of tons; but if filled with the material of the companion of Procyon it would weigh about 400 tons.

The largest star known is Antares, with a radius about 430 times the radius of the Sun (Fig. 8). Its size is so great that if the Sun were placed at its centre, the Earth would be only about half-way from the centre to the surface, and even Mars would be well inside the surface. The relative sizes of Antares and the Sun are shown in the diagram. We do not know the weight of Antares. But if we suppose it to be twenty times the weight of the Sun, it follows that the average density of the substance of Antares is about equal to that of the air in a fairly well-exhausted vacuum; in other words, sufficient of the material to fill an average-sized room would weigh only an ounce or two.

CHAPTER VIII

THE STARS—OUR BLOOD RELATIONS

IN the preceding chapter we have learnt something about the sizes, the weights and the candle-powers of the stars, but we have not yet considered of what they are made. To gain this information we must employ an instrument called a spectroscope, which can break up the light from a star into its constituent parts. If a beam of sunlight falls on a glass prism, the light after passing through the prism is found to be spread out into a coloured band in which we can recognise the sequence of colours in the rainbow: red, orange, yellow, green, blue, indigo and violet. The rainbow itself is formed by sunlight that has been broken up in a similar way by the drops of rain.

A beam of sunlight contains light-waves of many different wave-lengths; we may compare it to the complex sound that we hear when we listen to an orchestra, composed of many different notes—some high, which are of short wave-length, and others low, which are of longer wave-length. What the prism does is to bend the path of the beam of light so that it travels in a different direction; but the light-waves of short wave-length are bent through a bigger angle than the light-waves of long wave-length. The prism therefore sorts out the various wave-lengths and rearranges them in a definite sequence. The stellar spectroscope is an instrument in which one

or more prisms are used to break up the light from a star and to rearrange the various wave-lengths in their proper sequence.

The violet light, which is bent through the greatest angle, has the shortest wave-length, about 70,000 wave-lengths going to an inch; the red light, which is bent through the least angle, has the longest wave-length, about 35,000 wave-lengths going to an inch. But just as the human ear can only detect sounds that fall within a certain range of wave-length and fails to hear a note if its pitch is either extremely low or extremely high, so it is with the human eye. Light of wave-length shorter than the violet waves or longer than the red waves is not perceived by the eye. But our eyes are much more limited in their range of vision than are our ears in their range of hearing. For we can perceive sounds over a range of about eleven octaves—corresponding to a ratio of about 2,000 to 1 in wave-length; but our eyes can only perceive light-waves over a range of one octave, corresponding to a ratio of 2 to 1 in wave-length.

The radiations in a beam of sunlight which are of longer wave-length than the red light can be detected by their heating effect. If we allow the prismatic band of sunlight—or the spectrum, as it is called—to fall on a screen and place the bulb of a thermometer just outside the red end of the band, we shall find that a rise in temperature is recorded by the thermometer, showing that infra-red rays are present and that they have heating power. The radiations of shorter wave-length than the violet light can be detected by their actinic effect. If we

place a photographic plate (suitably screened from direct light) just outside the violet end of the band and develop it, we shall find that it has been heavily fogged, showing the presence of ultra-violet waves with great actinic power.

In 1814, Fraunhofer found that in the spectrum of sunlight every wave-length was not represented. When sunlight was passed through a fine slit before passing through the prism and was then brought to a focus, he found that the bright spectral band was crossed by a large number of narrow dark lines. These lines are generally known as Fraunhofer's lines. To understand how these are produced, I must say a few words about the spectrum of a simple chemical substance.

If we place a little common salt in a hot flame of coal gas and examine its spectrum, we shall not see a continuous band of prismatic colours, but just a few bright lines. This kind of spectrum—called a bright line or emission spectrum—is produced by a glowing gaseous vapour. If, for instance, we pass an electric spark between two iron terminals, there is incandescent vapour of iron in the hot region where the spark occurs; when we form its spectrum we see a series of bright lines.

The series of lines given by any particular substance shows that the substance is sending out light of certain wave-lengths only. Furthermore, just as each of us has a different finger-print and each finger-print is characteristic of the individual to whom it belongs, so the group of lines forming the spectrum of any element is characteristic of that element and serves to identify it. Some substances,

such as hydrogen, have a fairly simple spectrum containing only a few lines; others, such as iron, have a very complex spectrum, containing many hundreds of lines.

An incandescent solid sends out radiations of all wave-lengths and therefore gives a continuous band of prismatic colours for its spectrum. If the light from such a source is passed through a cool gas or vapour, which by itself would give a spectrum of bright lines, the spectrum now consists of a continuous bright background crossed by a number of dark lines that exactly correspond in position to the bright lines previously obtained. These dark lines are caused by radiations of certain wave-lengths being absorbed by the cool vapour. Such a spectrum is therefore called a dark line or absorption spectrum. The correspondence in position between the bright lines in the emission spectrum and the dark lines in the absorption spectrum indicates that the atoms of a gas can absorb exactly those radiations that they can also emit and no others. It should perhaps be mentioned that the darkness of the lines is purely relative to the adjacent bright background, just as the sun-spots appear dark in comparison with the brighter portions of the Sun surrounding them.

Let us now consider what is happening in the Sun, which we may regard as an average star. Radiation is welling up from the intensely hot interior towards the comparatively cool surface layers. Deep down in the interior the temperature is so high that the whole of the radiation is of extremely short wave-length, comparable to X-rays. As it works its way

outwards towards the surface, it is continually absorbed and re-emitted by atoms of various elements. As the temperature falls continuously from the centre to the surface, the radiation is gradually transformed into radiation of longer and longer wave-length, until at last we get the infra-red, visual and ultra-violet radiations that are emitted from the surface. Before reaching the surface, all wave-lengths in this range are present. The atoms of iron in the relatively cool outer atmosphere absorb from this radiation all those wave-lengths which are present in the spectrum of iron; similarly, the atoms of every other element present absorb each their own particular series of wave-lengths. The atoms, having absorbed these radiations, emit them again in all directions. The light that finally emerges has thus been robbed to a large extent of the wave-lengths associated with all these different sorts of atoms, because the radiations of these wave-lengths have mostly been scattered in other directions. The spectrum of sunlight consists therefore of the prismatic band, crossed by a multitude of dark lines corresponding in position to each one of these wave-lengths.

If we could screen off the direct light coming from the interior of the Sun, we should see the spectrum of the hot gaseous atmosphere. This spectrum should consist of a series of bright lines agreeing in wave-lengths with those of the dark Fraunhofer lines. A total eclipse of the Sun provides a suitable opportunity. The Moon, as it moves in front of the Sun, gradually cuts off its light. Just before the Sun is totally eclipsed a narrow bright crescent of

light remains around one edge of the Moon. We see then the Sun's outer atmosphere. The atoms in this atmosphere are absorbing radiations that come from the interior of the Sun and are emitting them again in all directions. The light that reaches us consists only of the radiations emitted by this atmosphere. The spectrum is found then to consist of bright lines on a dark background—the typical spectrum of a hot gas. This bright-line spectrum lasts for a few seconds only, until the advancing Moon has completely hidden the Sun's atmosphere. A portion of the Sun's spectrum, obtained in this way at the total eclipse of 1932, is reproduced in Plate XXII. The spectrum consists of a number of circular lines. Each one of these is an image of the bright crescent of the Sun formed by light of a definite wave-length. It will be noticed that some prominences were projecting from the Sun's limb. The stronger radiations in this portion of the spectrum are due to hydrogen, sodium, calcium and helium.

The spectrum of the Sun contains a large number of lines; somewhere about 16,000 were catalogued by Rowland. Many of the elements with which we are familiar on the Earth have been detected in this spectrum by their finger-prints. Fifty-seven known elements have been definitely detected in the Sun. The remaining thirty-five elements, which have not been definitely detected, include two elements which have not yet been found on the Earth; several elements whose spectra contain no strong lines in the range of wave-lengths which the Earth's atmosphere transmits; and several other elements

whose spectra have not yet been sufficiently investigated in the laboratory for identification to be possible. There remains the group of heavy elements, osmium, iridium, platinum, tantalum, gold, mercury, bismuth and polonium, none of which has been detected, though we should expect to find some of them unless they are present in very minute proportions. It is probable that the weight of the atoms of these heavy elements causes them to sink to a considerable depth in the Sun's atmosphere; this would make their detection impossible and would account for their apparent absence.

We conclude that we are not justified in asserting that any element found on the Earth is absent from the Sun.

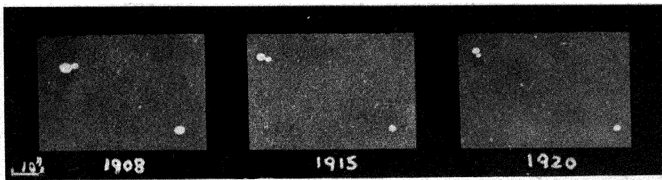
There is one element, helium, which was found in the Sun before it had been discovered on the Earth. At the total eclipse of the Sun in 1868 a strong line in the yellow was observed in the bright-line spectrum of the Sun's atmosphere; this strong line could not at that time be assigned to the spectrum of any known element. It was concluded that it must be produced by an unknown element, which was accordingly named helium after the Greek word for the Sun. It was not until 1895 that helium was discovered on the Earth. In that year the chemist Ramsay found that it was present in small quantity in the air we breathe and also in the mineral called uraninite. Helium was regarded as an extremely rare gas until some twenty years ago, when it was found to be a constituent of the natural gas from the oil wells in certain regions in the United States. It was possible to obtain it from this source in quanti-

ties sufficiently great to enable it to be used to inflate airships.

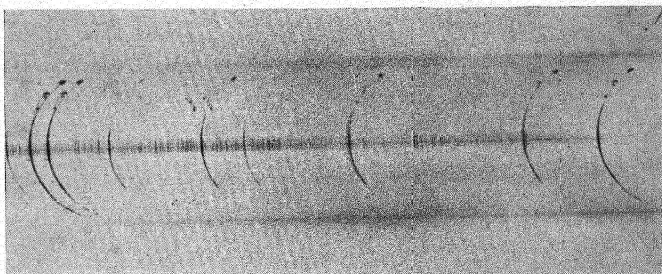
There are many stars whose spectra are exact counterparts of the spectrum of the Sun. Corresponding portions of the spectra of the Sun and of Alpha Centauri are shown in Plate XXII. Many other stars have spectra that bear no resemblance to the spectrum of the Sun. We find, however, that we can select a series of spectra each one of which shows only slight differences from the spectra that precede and follow it and such that with few exceptions the spectrum of any star can be matched against one of the spectra in this series. We can compare such a series with a moving picture; each picture shows but slight differences from the next, but there may be no correspondence at all between the first picture and the last.

When we have arranged the different types of stellar spectra in such a series, we find that we have arranged the stars in a sequence of progressively changing colour and temperature. If we could take a cool star and heat it up gradually, we should find that its spectrum would pass continuously through this series. We actually see such changes taking place in certain stars that are variable in brightness, these variations in brightness being accompanied by changes in temperature.

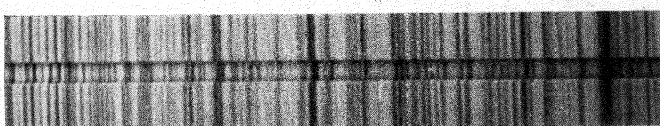
A giant red star, many thousands of times larger than the Sun in volume and of extremely low density, has a spectrum that is almost identical with the spectrum of a dwarf red star of small size and high density. The reason is that the nature of the spectrum is determined mainly by the tempera-



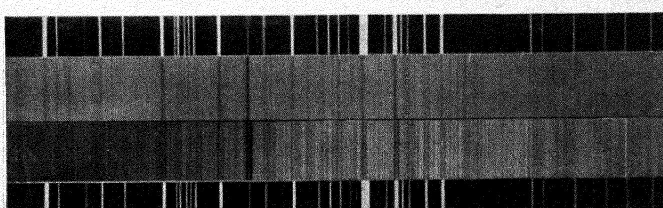
(*a*) PHOTOGRAPHS OF THE TWIN STAR, KRÜGER 60 (TOP LEFT-HAND CORNER), IN 1908, 1915 AND 1920, SHOWING ORBITAL MOTION.



(*b*) SPECTRUM OF SUNLIGHT AT TOTAL ECLIPSE OF AUGUST 31, 1932. A separate image of the bright crescent is given by the light of each wave-length. The strongest images are due to calcium, hydrogen, helium and sodium. (The photograph is a negative.)



(*c*) PORTION OF SPECTRA OF SUN (TOP AND BOTTOM) AND OF ALPHA CENTAURI (CENTRE).



(*d*) SPECTRUM OF ZETA URSÆ MAJORIS AT TWO DIFFERENT DATES. The lines in the lower spectrum are doubled.

PLATE XXII.

ture of the outer layers of the star and these temperatures for the giant and dwarf red stars are the same.

The surface temperatures of the hottest stars are about 60,000° C. and of the coolest stars about 2,000 degrees. The ratio of the temperatures is 30 to 1, but this ratio corresponds to a ratio in the energies given out by equal areas of surface of the two stars of 810,000 to 1. Whereas every square inch of the Sun's surface sends out energy at the rate of 62 horse-power, the hottest stars send out energy at a rate of somewhere about 500,000 horse-power from each square inch of surface and the coolest at a rate of considerably less than 1 horse-power from each square inch of surface.

The lines present in the spectra of the hottest and bluest stars are mainly due to hydrogen, helium, oxygen, nitrogen and silicon; lines due to the metallic elements are absent. In the spectra of the yellow stars, occupying the middle range of temperature, the lines due to helium, oxygen, nitrogen and silicon are weak or absent, and the lines of the metallic elements, such as calcium, iron, titanium, aluminium and manganese, are prominent. In the coolest stars we find evidence in the spectra of the presence of simple compounds, such as carbon monoxide, cyanogen, zirconium oxide and titanium oxide. It might be thought that these differences in spectra were related to differences in chemical constitution, and that stars like the Sun might be composed largely of metals, whilst the hottest stars might be composed largely of hydrogen and helium. This is not the true explanation of the differences in the spectra.

We have remarked that the spectrum of each element is characteristic of that element, just as a finger-print is characteristic of an individual. But actually matters are rather more complicated. If we place a little of an iron compound in the electric arc passing between two pieces of carbon, the spectrum will show the presence of iron: we can also obtain the spectrum of iron by passing a high-tension electric spark between two pieces of iron. But the two spectra do not correspond. Some lines appear in the spectrum of the spark that are not present in the spectrum of the arc; other lines are stronger in the spark spectrum and others again, that are present in the arc spectrum, are absent or weak in the spark spectrum. Both spectra are characteristic of iron and neither can ever be given by any other substance; depending upon the conditions under which the spectrum is produced, we may obtain the one type of spectrum or the other or even a spectrum which is intermediate between them. It would be a considerable complication for our finger-print experts if a criminal could have a dual personality—a Jekyll and Hyde existence—and give a different finger-print according to whether he was Jekyll or Hyde at the moment, and at times a finger-print which is a mixture of the two.

To account for this change of behaviour we must remember that an atom is a complicated structure forming a sort of miniature solar system; the nucleus of the atom corresponds to the Sun and the electrons moving in orbits around it correspond to the planets. The electrons are minute particles carrying a charge of negative electricity; the nucleus has a charge of

positive electricity sufficient to balance the combined negative charges of the electrons. The heavier the atom, the greater is the number of satellite electrons that it contains, and the more complicated is its structure.

Sometimes an atom loses one or more of its outer electrons. It is then said to be ionized. An ionized atom is positively charged and gives a spectrum which differs from that of the neutral atom. Atoms can be ionized by raising their temperature sufficiently. We may compare ionization with the process of breaking up a chemical compound into its constituent atoms by the action of heat. Just as by increase of temperature we can break up molecules of hydrochloric acid into atoms of hydrogen and atoms of chlorine, so also by a sufficient increase of temperature we can split atoms of neutral iron into atoms of ionized iron and electrons. The electric spark is considerably hotter than the electric arc; therefore in the spectrum of the spark, the lines that are due to ionized atoms of iron are prominent, and in the spectrum of the arc, the lines that are due to the neutral atoms of iron are prominent.

If the temperature is still further increased, many of the atoms will lose two electrons; such atoms are said to be doubly ionized, and they give rise to a spectrum that is different from the spectrum of either the neutral atom or of the singly ionized atom.

We are now in a position to understand how it is that the differences between the spectra of different stars are due mainly to differences of temperature. In the spectrum of the Sun, for instance, we find many lines that are produced by neutral atoms of

iron and many other lines that are produced by ionized atoms of iron; the lines produced by the neutral atoms are relatively stronger because the atmosphere of the Sun is not sufficiently hot to ionize most of the atoms of iron. If we pass through the sequence of stellar spectra from the Sun towards the low temperature side, we shall find that the lines due to ionized atoms of iron will completely disappear; on the high temperature side we find first that the lines due to neutral atoms of iron disappear and that at still higher temperatures the lines due to the ionized atoms disappear. The reason for the disappearance of these lines at high temperatures is that more and more atoms of iron lose two electrons as the temperature increases, until all the atoms of iron have become doubly ionized. But the doubly ionized atoms of iron have no lines in the range of wave-lengths normally accessible to observation. All evidence of iron therefore disappears from the spectrum of the star, although the atoms of iron in the atmosphere of the star are just as numerous as they were previously.

The very fact that it is possible to arrange the spectra of most of the stars into a single continuous series points strongly towards a uniformity in the composition of the stars—or at least in the composition of their outer layers. The elements which we may conclude from the evidence provided by stellar spectra are most abundant in the stars are hydrogen, silicon, sodium, magnesium, aluminium, carbon, calcium, iron, zinc, titanium, manganese, chromium, potassium, vanadium, strontium and barium. The elements which are the most abun-

dant in the crust of our Earth are oxygen, silicon, hydrogen, aluminium, sodium, calcium, iron, magnesium, potassium, titanium, carbon, chlorine, phosphorus, sulphur, nitrogen, manganese, fluorine, chromium, vanadium, lithium, barium, zirconium, nickel and strontium. Eight of the elements of this list, viz. oxygen, chlorine, phosphorus, sulphur, nitrogen, fluorine, zirconium, nickel, have spectra which are not well suited for estimating their abundance in the stars. The spectra of the hotter stars contain lines which are due to *ionized* oxygen, sulphur and nitrogen, and it is reasonably certain that these three elements are abundant in the stars. There seems, therefore, to be a remarkable parallelism between the composition of the Earth and the composition of the stars.

Not only are the stars in all parts of the Universe built from the same sorts of bricks—the atoms of the known elements—as those of which our Earth is made, but also there is an unexpected similarity in the relative proportions of the different varieties of bricks: the elements which are most abundant on the Earth are also on the whole the most abundant in the stars. We may therefore assert with some justification that the stars are our blood relations.

CHAPTER IX

TWIN STARS, PULSATING STARS AND NEW STARS

IN this chapter we shall consider three particular classes of stars which are of special interest—twin stars, pulsating stars and new stars.

Twin Stars

We have seen already that some stars, such as Krüger 60 (Plate XXII), are twin systems, for the two stars are visible in the telescope, and by repeated observations extended over a sufficient length of time the motion of the two stars about each other can be detected. Two stars may appear in the telescope as a twin system merely because they lie nearly in the same line of sight, though they are at very different distances from the Earth. Such optical pairs, as we may call them, will show in time motion relative to each other, because of the motion of each star in space. But the relative motion of one star with respect to the other will be in a straight line. It will not be curved as it must be when the stars form a true twin system. It is only when curved paths, due to orbital motion, have been detected that a pair of stars can be regarded as a twin system. The time taken for each star to go once round its orbit ranges for different systems from several years to many thousands of years. The distance apart of the two stars is the main controlling factor; when they are very far apart, their mutual gravitational

pull, which determines how fast they move, is weak. If, for instance, the two stars are each as massive as the Sun, they will take 10 years to go once round their orbit if their average distance apart is 540 million miles; 100 years if it is 2,500 million miles; and 1,000 years if it is 12,000 million miles.

A twin star which appears in the telescope as two stars is called a visual binary star. We do not know of any visual binary star in which the components move completely round their orbits in a shorter time than about 5 years. It does not follow that there may not be twin systems which are circling about each other in periods of less than 5 years. In any such system, the two stars must be comparatively near together (less than four times the distance of the Earth from the Sun) to move so rapidly. Because of the great distances of the stars we are unable to distinguish the slightly different directions in which the light from two such close stars reaches the eye. The star may be a twin, but even in a powerful telescope it appears as a single point of light.

It would therefore seem that, if there are twin systems in which the two stars are close together and in rapid motion about one another, we shall not be able to learn anything about them. Fortunately, however, there are several methods by which we can recognise these close twin systems and learn something about them. There is, for instance, a star called Algol, a bright star of the second magnitude in the constellation of Perseus, which shines with a practically steady light for about 60 hours; its brightness then commences to decrease and at the

end of 5 hours it is only one-third of its normal brightness. It then commences to brighten again and 5 hours later has returned to its original brightness, at which it stays for another 60 hours, when the fading repeats itself. The changes in the brightness of the star were known of old to the Arabian astronomers, who gave it the name Algol, meaning the demon star. John Goodricke in the eighteenth century showed that the changes in brightness occurred with perfect regularity.

The explanation of the inconstancy in the light of Algol is that the star is a twin system, though it appears in the telescope to be merely a single star. The two stars move in an orbit which is nearly in the line of sight and one star is much brighter than the other. Once in each revolution the faint star passes in front of the bright star and partially eclipses it. As soon as the eclipse commences, we see Algol begin to fade in brightness. As long as more and more of the bright star is being hidden, the fading continues; then, as the faint star passes away from the face of the brighter, the light increases. Half a revolution later, the bright star will partially eclipse the faint one. The one star is so much brighter than the other that we cannot by eye detect any fading when the faint star is eclipsed, though careful measurements reveal that there is a very slight fading.

Many stars are known whose light is variable because they are really twin systems and each star alternately eclipses (or partially eclipses) the other. These twin systems are of great interest because from a careful study of the light variations we can

learn a good deal about the sizes of the stars and their relative brightness.

In Fig. 11 are shown drawings to scale of three

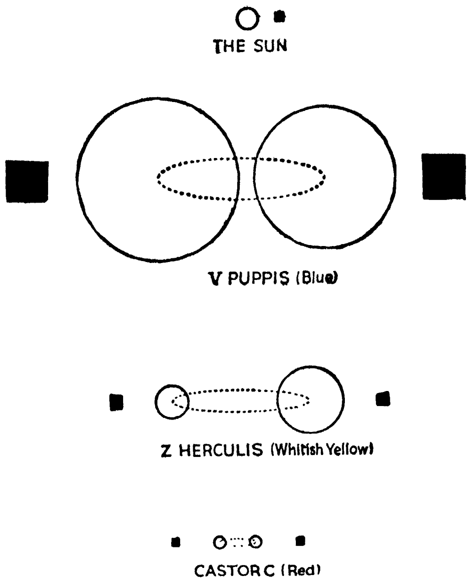


FIG. 11.—Relative sizes of typical twin stars. The relative orbits, as they appear from the Earth, are shown by the dotted lines. The areas of the black squares indicate the relative weights of the stars. The Sun is shown to scale; the orbit of the Earth around the Sun is nearly 12 times the size of the relative orbit of V Puppis, and is too large to be shown in this diagram.

typical twin systems; the orbit of the smaller star relative to the larger, as seen from the Earth, is represented as a dotted line. The size of the Sun on the same scale is shown for comparison. The colours of the three systems are respectively blue,

whitish yellow and red. These typical systems illustrate the general rule that the blue stars are large and massive; the yellow stars are comparable with the Sun; the red stars are of small size and mass. In the case of each of these systems, the orbits of the one star with respect to the other are much smaller than the orbit of the Earth about the Sun. It is because of the smallness of the orbits that we are unable to distinguish the two stars even with the aid of a powerful telescope.

If the orbits of the systems shown in Fig. 11 were tilted so as to make a greater angle with the line of sight, the orbit would appear more nearly circular and, if the angle is sufficiently large, eclipses will no longer occur, but the one star will pass above or below the other as seen from the Earth. Variation in the light will no longer be seen and we shall no longer have this indication of the twin nature of the system. There is, nevertheless, yet another way in which it may be possible to detect the presence of two stars.

In Plate XXII portions of the spectra of the Sun and of Alpha Centauri are shown. Line by line they correspond to each other, but every line in the spectrum of Alpha Centauri is displaced slightly from the corresponding line in the spectrum of the Sun. Such displacements of the lines of the spectrum of a star are produced by a motion of the star in the line of sight towards us or away from us. If, for instance, the star is moving towards the Earth, the waves of light sent out towards us are slightly crowded together by the motion of the star. The wave-length of the light is therefore effectively short-

ened; in other words, the light appears slightly bluer than it would have done had the star been at rest. The lines in the spectrum of the star are therefore all slightly shifted towards the blue, or short wave-length region. Similarly, if the star is moving away from us, the waves are slightly spread out. They are therefore reddened slightly and the lines in the spectrum of the star are all displaced a little towards the red or long wave-length region.

The spectrum of the star Zeta Ursæ Majoris at two different dates is shown in Plate XXII; the star spectrum is the central band, and above and below it a terrestrial spectrum is photographed for comparison, for the purpose of identifying the lines. The lines in the lower spectrum of the star correspond exactly to lines in the upper spectrum. But in the lower spectrum each line appears doubled. Observations of this star show that each line in the spectrum first opens and appears double, and then closes again and appears single with perfect regularity. We see here the effect of two stars moving in orbits about their centre of gravity. When the two stars are at the extreme positions in their orbits, one has a relative motion towards us and the other a motion away from us. Corresponding lines in the spectra of the two stars are therefore slightly shifted in opposite directions. We actually see a composite spectrum formed by the spectra of the two stars superposed. Each line in this spectrum therefore appears double. But when one star passes above or below the other, so that each star is moving at right angles to the line of sight with the same speed towards or away from us, corresponding lines in the

two spectra fall in exactly the same position and the composite spectrum appears to be the spectrum of a single star.

The two stars in the system of Zeta Ursæ Majoris do not differ greatly in brightness. But in some twin systems one star is much fainter than the other, and then only the spectrum of the brighter star is seen. The orbital motion of the star causes all the lines in the spectrum to swing backwards and forwards; the lines of the terrestrial comparison spectrum form the basis of comparison for detecting the to-and-fro movement of the lines.

Thus there are various ways of detecting the existence of twin systems. Of the stars visible to the naked eye, it appears that at least one in five is a twin system; for the fainter stars, information is necessarily incomplete, though there does not seem to be any reason why twin systems should be less common amongst these stars than amongst the bright ones. We may therefore conclude that twinning is a common phenomenon amongst the stars.

Some stars are more complex. The bright naked-eye star, Castor, appears in the telescope as a twin star. When the spectra of these two stars are photographed, we find that each of them is a close twin. One pair describes its orbit in about 3 days, the other in about 9 days. The two pairs revolve about each other in somewhere about 300 years. In addition, the telescope reveals a faint star which is also a member of the same system, and which is itself a close twin. This faint star must move round the other stars in a period of many thousands of years. Thus, whereas with the naked

eye we see only one star, there are actually six stars involved in the system.

Pulsating Stars

We have recognised some stars as twins because their brightness is not constant, but varies in a regular periodic manner. But variation in the brightness of a star is not necessarily an indication that the star is a twin system. Some stars which are single stars vary in brightness; in some cases in a perfectly regular manner, in others in an irregular manner. We know very little about the causes of the irregular variations. We have remarked that the recurrent ice-ages and warm periods on our Earth, of which we have proof from geological evidence, were probably caused by small fluctuations in the output of energy from the Sun. The Sun would therefore seem to be a star whose light varies slowly and irregularly by a small amount.

Of particular interest to the astronomer is a class of stars whose light varies in a perfectly regular manner. These stars are called Cepheid variables because the first star of this type to be discovered was the star Delta Cephei. The sequence of changes of brightness of such stars is of one general type and can be illustrated by the case of Delta Cephei. The complete sequence of changes takes about $5\frac{1}{2}$ days for this star. Starting at the time of greatest brightness, the star fades gradually during 4 days until it is only about half as bright as it was initially. It then commences to brighten again at a more rapid rate than it faded, so that in $1\frac{1}{2}$ days it has regained its initial brightness. The fall in brightness

always takes place more slowly than the rise in brightness. The complete sequence of changes is completed in a time which ranges for different stars from several hours to about a couple of months.

The changes in brightness of a Cepheid variable are attributable to a regular pulsation of the whole star. The star swells up and then contracts again with perfect regularity; it may be compared to an inflated rubber balloon—which is blown up, then partially deflated, blown up again, and so on in a perfectly regular manner. The difference between the radius of the star when it is most distended and the radius when it is smallest is generally somewhere about one-tenth of the mean radius, but may be as large as one-quarter.

We can obtain direct evidence that a Cepheid star is pulsating by photographing its spectrum. When the star is expanding, the surface of the star that is facing us is moving towards us and the lines in its spectrum are therefore all displaced and have wave-lengths which are somewhat shorter than the normal. When the star is contracting, the surface is moving away from us and the spectrum lines are shifted slightly in the opposite direction, the wave-lengths then being somewhat longer than the normal. All the lines in the spectrum therefore swing together slightly backwards and forwards in synchronisation with the pulsation of the star. But it was exactly this behaviour of the lines that we interpreted above as evidence of a twin system in which one star was much brighter than the other. This interpretation cannot be applied to the Cepheid variables, however, for two reasons. In

the first place we find that the size of the orbit comes out to be smaller than the bright star, which is a *reductio ad absurdum*; and, in the second place, the changes in brightness are accompanied also by changes in the colour and in the temperature of the star, indicating that the pulsation is related to the physical properties of the star.

The Cepheid variables are all giant stars, large in size, low in density, of very great candle-power and generally much more massive than the Sun. In the table below, data for several typical stars are summarised. The following details are given: the name of the star, the period of a single pulsation, the luminosity or candle-power in terms of that of the Sun as unit, the radius in terms of the radius of the Sun, the total change in radius in millions of miles, the mass in terms of the mass of the Sun as unit, and the mean density in terms of the density of water as unit.

	Period of pulsation Days.	Luminosity (Sun = 1).	Mean Radius (Sun = 1).	Change in Radius (millions of miles).	Mass (Sun = 1).	Density (water = 1).
RR Lyræ .	0·6	125	6	0·21	5	·031
SU Cassiopeiæ	2·0	260	13	0·37	6	·004
Polaris . .	4·0	460	22	0·19	8	·0011
δ Cephei .	5·4	700	26	1·6	11	·0008
η Aquilæ .	7·2	1,000	35	2·2	13	·0004
ζ Geminorum .	10	1,700	43	2·3	18	·0003
X Cygni .	16	3,200	70	7·6	26	·00011
Y Ophiuchi .	17	3,500	72	2·2	28	·00011
l Carinæ .	36	9,600	116	10·7	50	·00004

The stars in this table have been arranged in the order of increasing period of pulsation. It will be

noticed that this arrangement has placed them also in the order of increasing candle-power, increasing size, increasing mass and decreasing density. This cannot be the result of chance but must be connected in some way with the physical nature of this particular type of star.

The relationship between the period of pulsation of a Cepheid variable star and its candle-power has proved of the highest importance in astronomy. We notice that the greater the luminosity of the star, the longer is the time taken for a single pulsation. So close is the correlation between the two quantities that we need only measure the time of the pulsation—or, in other words, the time in which the light of the star varies through one complete cycle—and we know at once the candle-power of the star. Comparing the candle-power with the apparent brightness of the star, we are able at once to deduce its distance. In this way we are provided with a powerful means of exploring space, for we see from the third column of the above table that the Cepheid stars are intensely luminous and can consequently be seen at very great distances. For instance, the last star in the above table, if it were at a distance of 50,000 light-years, would appear as a star of the eleventh magnitude, easily visible in a six-inch telescope. Suppose we observe the star, comparing its brightness with the brightness of several neighbouring stars, over an interval of some months; we find that it is pulsating in a period of 36 days. We can conclude at once that its candle-power is 9,600 times the candle-power of the Sun, and therefore, since it appears as a star of the

eleventh magnitude, that its distance must be 50,000 light-years. When we remember that direct measurements of stellar distances greater that 500 light-years are practically meaningless because errors of observation cannot be reduced below a certain small value, we shall realise what a powerful instrument the Cepheid variable is for the exploration of space. In a later chapter we shall see to how great an extent our knowledge of the size of the Universe depends on this property of the Cepheid variable stars.

New Stars

The third class of stars of particular interest is the small group of stars known as new stars or novæ. A nova is a star that undergoes a rapid and considerable increase in brightness, which may be anything from several thousand-fold to several million-fold; after the peak of the flare-up has been reached, the brightness diminishes again, usually rapidly at first and then more and more slowly. The name of " new star," suggesting the birth of a star that did not exist before, is therefore misleading. But the name was given at a time when the appearance of a nova was viewed with wonder and when it was believed that a star had come into existence where no star previously existed. The surprise with which the appearance of a brilliant new star in the year 1572 was regarded can be judged from the account given by the great Danish astronomer, Tycho Brahe. The following is a translation of a portion of his account of this star, entitled *De Nova Stella* :

"Last year (1572), in the month of November, on the eleventh day of that month, in the evening, after sunset, when according to my habit, I was contemplating the stars in a clear sky, I noticed that a new and unusual star, surpassing the other stars in brilliancy, was shining almost directly above my head; and since I had, almost from boyhood, known all the stars of the heavens perfectly (there is no great difficulty in attaining that knowledge), it was quite evident to me that there had never before been any star in that place in the sky, even the smallest, to say nothing of a star so conspicuously bright as this. I was so astonished at this sight that I was not ashamed to doubt the trustworthiness of my own eyes. But when I observed that others, too, on having the place pointed out to them, could see that there was really a star there, I had no further doubts. A miracle indeed, either the greatest of all that have occurred in the whole range of nature since the beginning of the world, or one certainly that is to be classed with those attested by the Holy Oracles, the staying of the Sun in its course in answer to the prayers of Joshua, and the darkening of the Sun's face at the time of the Crucifixion."

The star which Tycho Brahe observed was, when at its greatest brightness, much brighter than any other star in the sky, brighter also than Jupiter and nearly as bright as Venus. It faded gradually and ceased to be visible to the naked eye about 16 months after it had flared up. In the position in the sky where it appeared only very faint stars are now to be found, and it is not possible to identify Tycho's star with certainty. It may be concluded

FIG. 12.—Tycho Brahe and the New Star of 1572. (From the English edition of *De Nova Stella*, London, 1632.)

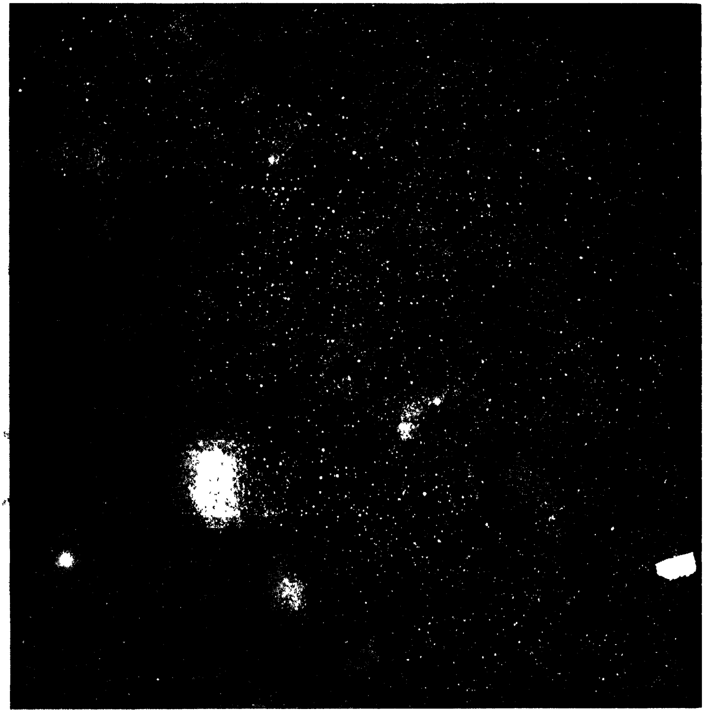


Plate XXIII.—Portion of the Milky Way in the Constellation of Aquila, showing the Two Branches separated by a Rift relatively devoid of Stars.

that at its greatest brightness it was not less than 16 million times brighter than it now is.

Another brilliant nova appeared a few years later in 1604 and was observed, amongst other astronomers, by Kepler, whose patient investigation of Tycho Brahe's observations of the planets led to the discovery of the celebrated laws of motion of the planets, which made it possible for Newton to discover the law of gravitation. The nova of 1604, though not so bright as Tycho's nova, became brighter than Jupiter or than any other star. It remained visible to the naked eye for about 16 months.

The next brightest nova of which we have record appeared comparatively recently, in June 1918, and was discovered independently by many observers. The rise in brightness of this star was rapid. On June 5 it was of normal brightness. At its discovery on June 8, it had increased in brightness ten-thousand-fold. The next evening it was the brightest star in the whole sky, with the exception of Sirius and Canopus.

The most recent nova was discovered on December 13, 1934, by Mr. J. P. M. Prentice, a young British amateur astronomer. The star was of about the third magnitude when it was discovered, but subsequently brightened to the first magnitude. On photographs taken before the outburst, it appeared as a very faint star, the total increase in brightness being about 400,000-fold. The star remained visible to the naked eye for about 4 months, after which there came a rapid fall in brightness.

The great increase in brightness which occurs

when a nova flares up must be due to one or both of two factors—to an increase in the surface temperature of the star, which is equivalent to an increase in the candle-power per square foot of the surface of the star, or to an increase in the total surface area of the star. We can estimate the surface temperature of the nova from its spectrum and there is no evidence of any abnormally high temperature at maximum. So although in general we have little or no information about the temperature before the flare-up, we can conclude that the brightening must be due in the main to increase in surface area. In other words, the outburst is accompanied by a rapid and extensive swelling up of the star. If, for instance, the increase in brightness at the flare-up is a million-fold, the star must swell up so that its radius becomes 1,000 times its initial value if there is no change in surface temperature, but if there is a five-fold increase in temperature the radius will only be 40 times its initial value.

At the peak of the outburst the star throws off its outer shell of atmosphere. This gaseous shell travels outwards from the star with a velocity usually of some hundreds of miles per second. In the case of the nova in the constellation Aquila, which flared up in June 1918, the expanding shell of gas can still be photographed, growing uniformly as it continues to recede from the star with the high velocity of about 1,100 miles a second.

After the peak is passed, the nova slowly sinks again. This shrinkage is accompanied by a considerable increase in temperature. There is some doubt as to the final state of the star, because its faintness makes it

difficult to learn much about it. It seems probable that it finally becomes a small star of very high density, possibly comparable to the small, dense companion of Sirius.

The intrinsic luminosity or candle-power of a nova when at its brightest is very high, being some ten or twenty thousand times brighter than the Sun. Novæ have been detected in some of the distant stellar systems, and they have provided valuable corroborative evidence of the distances of those systems inferred from the observation of Cepheid variables.

It is only when a nova is within a distance of a few thousand light-years that it becomes a conspicuous naked-eye object. If a star at a distance greater than 10,000 light-years becomes a nova, it is not probable that it could be seen with the naked eye. But many such outbursts of distant stars have been detected on astronomical photographs. Bright naked-eye novæ have appeared of recent years in 1918, 1920, 1925 and 1934. The true frequency of nova outbursts is not to be judged from these somewhat rare and spasmodic appearances. It seems probable that in our Milky Way system of stars, the number of novæ which flare up averages about 30 a year. The total mass of this system is of the order of 2,000 million times the mass of the Sun. As there is not a wide range in stellar masses, we may conclude that in the course of a few thousand million years there will be as many nova outbursts as there are stars. At the present time astronomers are somewhat divided in opinion as to the ages of the stars; some favour a relatively short

life of a few thousand million years (comparable with the age of the Earth); others favour a much longer life. Whichever view we accept, we must conclude that on the average every star passes through a nova outburst at least once in its life-history. It may be that some stars pass through this stage many times during their lifetime. If the stars have the longer lifetime mentioned above, this would seem to be inevitable. It is therefore not improbable that the nova flare-up is a sort of distemper which few stars are likely to escape.

The cause of these remarkably violent outbursts, which are accompanied by an enormous expansion of the star and a vastly increased output of energy, is not known for certain. From one point of view they are of special interest to us; they provide our only opportunity of seeing the evolution of the stars actually in progress. For the most part this evolution takes place with such extreme slowness, judged by ordinary human standards, that if we could see the stars as they appeared to our first parents we should be able to detect little or no change in the vast majority of them.

The most plausible theory that we can suggest at the present time supposes that the star, during the slow progress of its evolution, arrives at a stage when its equilibrium becomes unstable. When this occurs, there will be a rapid transition to a new state of stability. We can illustrate in a crude way by a jug standing on a flat table. If the jug is tilted slightly and then released, it will fall back to its first position; it is said to be in stable equilibrium. But if it is tilted more than a certain amount, it will no

longer return to its former position but topples over and takes up a new position of stable equilibrium on its side.

In collapsing from one stable position to another stable position there is a sudden release of gravitational energy within the star. The outrush of this energy will temporarily distend the star and increase its candle-power. When the energy has been released, the star settles down in a new stable state as a small star of very high density.

Our own Sun has not passed through the nova stage. Some astronomers believe that it is showing incipient signs that it is approaching this stage. Even if this were the case, the outburst might not occur for millions of years yet—a short interval in the life-history of a star. But should the Sun become a new star, everything on the Earth would very quickly be burnt and in the course of a few hours the Earth itself would become merely a cloud of hot gases; the Sun might even swell up to such an extent that it would swallow the Earth. A sudden death by heat is one possible end of our Earth.

CHAPTER X

OUR STELLAR UNIVERSE

In the preceding four chapters we have considered the stars in general; how their distances, luminosities, masses and temperatures are determined and how one star differs from another. We have also discussed in more detail some special classes of stars of particular interest. But we have not yet considered how the stars are distributed in space. Are they scattered at random, as though sprinkled through space from a vast celestial pepper-pot, or is there any indication that the Universe has a definite structure? The first serious attempt to answer this question was made about 150 years ago by William Herschel, who has been called "the father of modern astronomy."

If we look carefully at the sky on a dark moonless night, we shall notice that the few thousand stars which can be seen by the naked eye are not by any means distributed uniformly over the sky, but that they are considerably more numerous in or near the Milky Way than in the other portions of the sky. The Milky Way or Galaxy is the name given to the broad belt of faint luminous haze which encircles the whole sky. In the northern sky it passes within about 30° of the north pole, runs through the constellations of Cassiopeia, Perseus and Auriga to the horns of Taurus. Then it passes between Orion and Gemini, through Monoceros to Argo, the Southern Cross and the feet of the Centaur. Here it

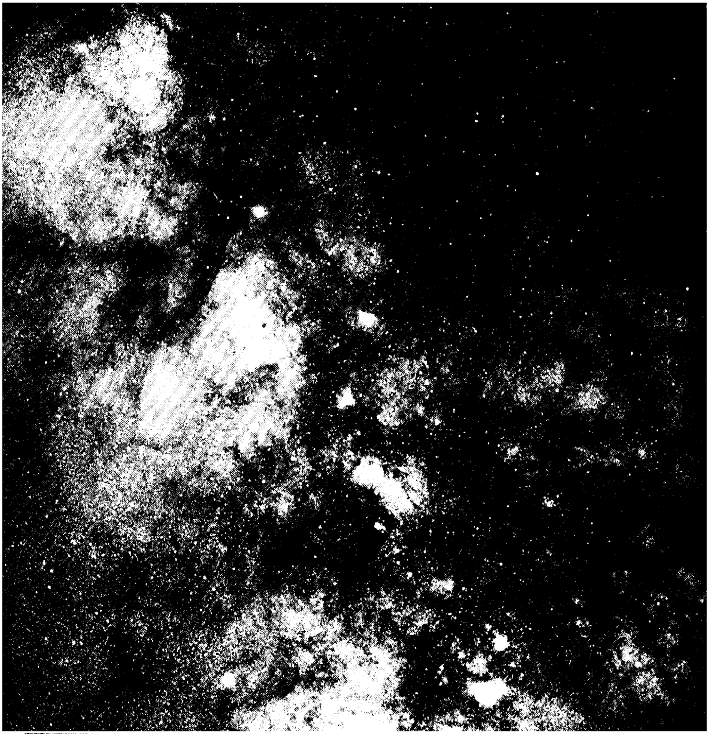


PLATE XXIV.—PORTION OF THE MILKY WAY IN THE CONSTELLATION OF SAGITTARIUS.

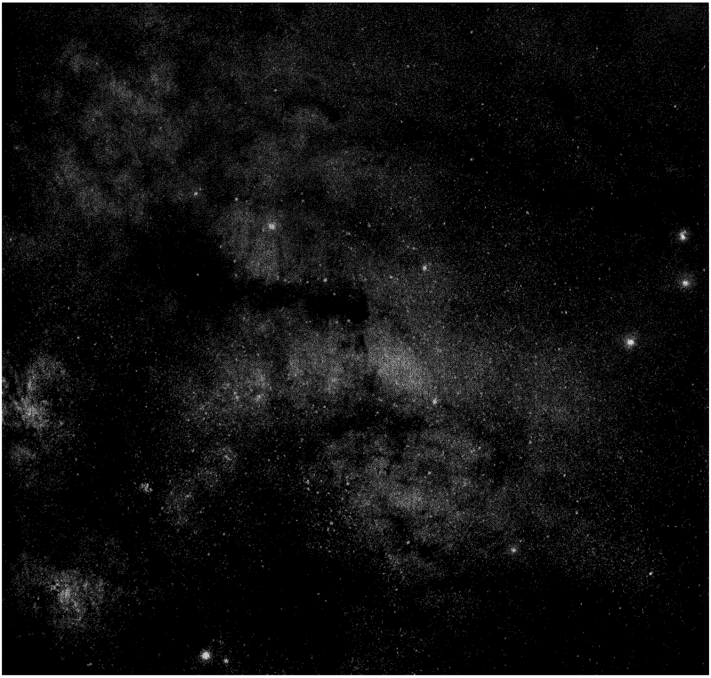


Plate XXV.—Portion of the Milky Way in the Constellations of Scorpio and Ophiuchus.

divides into two branches, the brighter of which passes through Ara, Scorpio, the bow of Sagittarius and Aquila to Cygnus, where it rejoins the other branch. A portion of the Milky Way in the constellation Aquila is reproduced in Plate XXIII; the two branches, with the dark rift between, are shown.

The Milky Way has had an important place in the mythology of many primitive peoples, and has often been regarded as the road traversed by the souls of the departed. Longfellow relates how, when the wrinkled old Nokomis nursed the little Hiawatha:

> "*Many things Nokomis taught him*
> *Showed the broad, white road to heaven,*
> *Pathway of the ghosts, the shadows,*
> *Running straight across the heavens.*"

The concentration of the bright stars towards the Milky Way suggests that we may there find the clue for unravelling the problem of the structure of the Universe. When William Herschel first developed an interest in astronomy he bought a copy of Ferguson's *Astronomy*, the best text-book of the day, which passed through many editions. The almost complete ignorance about the stars at that time is reflected in Ferguson's book, in which twenty-one chapters are devoted to the solar system and one chapter only to the stars. The then current knowledge about the Milky Way is summed up in one brief paragraph:

"There is a remarkable tract round the Heavens

called the Milky Way from its peculiar whiteness, which was formerly thought to be owing to a vast number of very small stars therein; but the telescope shows it to be quite otherwise; and therefore its whiteness must be owing to some other cause."

This is not much more informative than the old Greek view that the Milky Way arose from a few drops of milk which the infant Hercules let fall from the bosom of Juno.

When Herschel turned the telescopes of his own making, which far surpassed in optical quality any telescopes previously made, upon the Milky Way, he found that Ferguson's description was wrong and that Bacon's statement was correct that "the Milky Way in the sky . . . is a meeting or knot of a number of small stars, not seen asunder but giving light together." Herschel describes how "the glorious multitude of stars of all possible sizes that presented themselves here to my view was truly astonishing."

Herschel found that the number of stars brighter than any given limit of apparent magnitude seen in the field of his telescope was greatest in the Milky Way and that the number decreased progressively with increase in distance from the Milky Way; the disparity in numbers becomes greater the fainter the stars. If we divide the sky into small squares measuring one degree each way, then in the Milky Way there is on the average one star visible to the naked eye in every 8 squares; but at a distance of 90 degrees from the Milky Way, there is only one such star in every 27 squares. But when we consider stars down to magnitude 20, we find from recent counts of stars that there is an average number

of 40,000 in each square in the Milky Way, but only 1,200 in each square at a distance of 90 degrees from the Milky Way.

Herschel's investigations led him to the conclusion that the stars are grouped in space in the form of a flattened disc, like a millstone, with the radial extension of the system much greater than its thickness. He believed that the Sun was situated somewhere near the centre of this system. In the direction of the Milky Way we look through the system to its most distant limits, but the system is so flattened that in a slightly different direction we look through a much smaller depth. The large number of faint stars to be seen in the Milky Way is a consequence of the great extension of the system in the radial direction.

The Milky Way is by no means uniform in brightness, nor is the distribution of the stars to be seen within it at all uniform. There are numerous local aggregations of stars, or star-clouds, in the Milky Way. The brightest region, containing the densest aggregation of stars, is in the constellation of Sagittarius, in the southern sky. A portion of this region is shown in Plate XXIV; the irregular distribution of the stars is well illustrated by this photograph. Cepheid variables have been found in some of the star-clouds, and that has made it possible for their distances to be estimated. The star-clouds are all very remote from us; some of the distances which have been measured are as great as 30,000 light-years. It would seem probable that the Galaxy extends to distances much greater than this, for we may suppose that there are more distant star-clouds,

hidden from view by the nearer ones. We shall see that there are methods by which a reasonably good estimate of the total dimensions can be obtained.

In many parts of the Milky Way we find not stars only but hazy patches of faint greenish light, which the most powerful telescope will not separate into faint stars. These patches of delicate wispy light are called nebulæ, from the Latin word for a cloud. The most beautiful is the Great Nebula in Orion (Plate XXVI), which can be seen with the naked eye as the faint hazy patch in the middle of the dagger of Orion. This nebula was mentioned by Peiresc in 1611, and was rediscovered by Huyghens in 1656. Huyghens believed that it was a "hiatus in the sky, affording a glimpse of more luminous regions beyond."

The nebulæ were studied in great detail by William Herschel, who had catalogued 2,500 of them by the year 1802. Herschel was at first of the opinion that they were aggregations of very distant stars. Just as to the naked eye the Milky Way appears as a hazy nebulosity which the telescope resolves into faint stars, so, thought Herschel, the nebulæ might be much more distant aggregations of stars, that were beyond the power of his telescope to resolve. But when in 1790 he discovered a star surrounded by a faint luminous atmosphere of a circular form, he concluded that the nebulæ were rarefied clouds of gas. Direct proof of the gaseous nature of the nebulæ was not obtained until 1864, when Sir William Huggins first observed their spectra. He found that their light does not contain all the colours of the rainbow but consists of a number of discrete radia-

tions. This is the type of spectrum given by a glowing gas of low density, as we have already seen.

The gaseous nebulæ appear green because the light which they emit in the visual region of the spectrum consists mainly of two radiations in the green. The spectral lines corresponding to these radiations have never been found in the laboratory. When they were discovered in the nebulæ, they were attributed to an unknown element which was called *nebulium*, following upon the precedent of calling by the name helium the element responsible for the strong unknown line in the flash spectrum of the Sun. But as physical investigation unravelled the structure of the atoms of the various elements, it was realised that there was no gap between the known elements remaining to be filled by nebulium. The only possible alternative explanation of the strange lines was that they were emitted by a known element, which was under conditions which the physicist had not reproduced in his laboratory. The conditions in the nebula are, in fact, different from those obtainable in the laboratory; the density of the nebulous gas is not more than one-millionth that of the residual gas left in the most perfect vacuum that can be obtained with the aid of modern high-vacuum technique, and the radiation from the stars, which is absorbed and emitted again by the nebulosity, is extremely weak. The atoms are therefore in a much more quiescent state than is possible in the laboratory. The secret of nebulium has now been unravelled, for theoretical calculations have established that the green lines are produced by

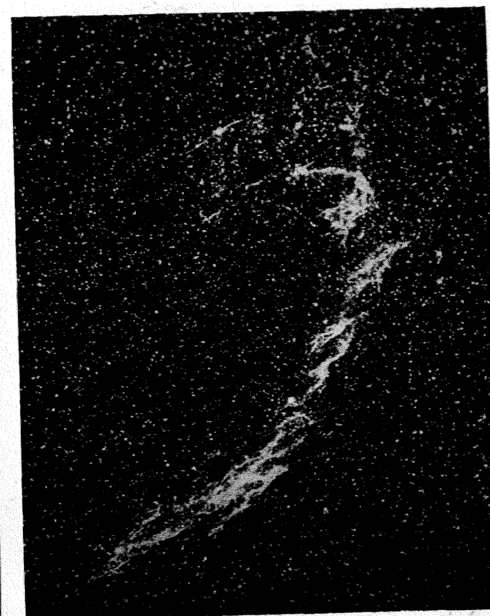
doubly ionized atoms of oxygen, i.e. by atoms of oxygen which have lost two electrons.

The nebulæ are not self-luminous but shine by the light of the stars which are embedded in them. This is more clearly apparent in the case of some nebulæ than others, but it seems certain that all the green nebulæ shine in this way. The small constellation of the Pleiades provides the clearest illustration. A photograph with a moderate exposure shows a bright patch of nebulosity around each one of the brighter stars; a photograph with a long exposure shows that much fainter nebulosity extends throughout a considerably larger area.

But though it is the light of the stars embedded in the nebulæ which causes them to shine, they do not merely reflect the light, in the way that the Moon shines by reflecting the light of the Sun, or scatter it, in the way that the light from motor-car headlamps is scattered by a foggy atmosphere. The light from the stars is actually absorbed by the atoms in the nebula and is re-emitted in radiations of different wave-length. We can compare the action of the nebulæ to that of the luminous paint on the hands of a watch, which absorbs light but emits a different kind of light. It is only the blue stars of high temperature that can stimulate the nebulæ to shine; the Sun and even the giant red stars such as Antares or Betelgeuse cannot do so, because their temperatures are too low.

Another feature of the Milky Way which attracted Herschel's notice was dark patches, looking very much like small clouds. In some of the densest star-clouds in the Milky Way there are what appear

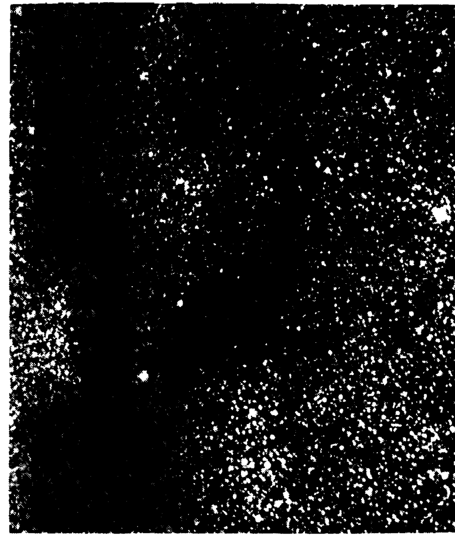
(*a*) The Great Nebula in Orion.



(*b*) Diffuse Nebula in Cygnus.

Plate XXVI.

(a) Absorbing Cloud in Ophiuchus.



(b) Absorbing Cloud in Aquila.

Plate XXVII.

to be gaps, with few or no stars in them. The most striking example is one called the "Coalsack," adjacent to the Southern Cross, which is easily visible to the naked eye and has the appearance of a small cloud hiding the portion of the Milky Way behind it. Herschel thought that these vacant regions were lanes or channels through the star-clouds. A long and careful study of these dark patches was made by Barnard, who catalogued nearly two hundred of them. Some examples of these dark regions are shown in Plate XXVII; many others will be seen in Plate XXV. That there should be so many vacant lines through the great depth of the star-clouds in the Milky Way pointing directly to the Earth is so exceedingly improbable that another explanation must be found. Barnard suggested that there are opaque clouds between us and the Milky Way. These clouds screen from us all the stars which lie behind them and we see only those stars which lie between us and the clouds. Some of the clouds must be relatively near, for not a single star can be seen within their boundaries; others are more distant and we see the foreground stars projected on them. Some are small and others of enormous extent.

We may have dark gaseous clouds which are similar in every respect to green nebulæ, but are not luminous because they do not contain any very hot stars. But such clouds must be almost completely transparent, because their density is extremely small. Light passing through a gaseous nebula extending over a distance of one thousand light-years would be less absorbed than in passing through

the atmosphere of the Earth. The opaqueness of the obscuring clouds must be due to the presence of extremely fine dust. Dust particles comparable in size with the wave-length of light have very great obscuring power. If the average amount of dust in the cloud is only one-fifty-thousandth of an ounce in each square inch of cross-section, the cloud will be completely opaque, whatever its thickness may be. It is probable that the clouds consist of a mixture of dust particles of various sizes, and they may even contain small meteoric stones. We have mentioned that many small meteors enter the atmosphere of the Earth from outer space.

The opaque clouds and the luminous nebulæ frequently occur in close association with one another. A striking example is provided by the nebulous region around Rho Ophiuchi (Plate XXVIII), where there is a conspicuous dark lane and at its head an extensive region of luminous nebulosity. It is probable that the two classes of nebulæ are essentially the same; the presence of the fine dust particles will make any nebula opaque unless there are high-temperature stars suitably placed near its surface to illuminate it. Some of the bright nebulæ, however, such as the diffuse nebula in Cygnus (Plate XXVI), show no traces of absorbing dust and may be almost, if not entirely, gaseous.

We have mentioned that over a great portion of its extent the Milky Way is divided into two branches. The appearance of two branches is caused by the existence in the central regions of the Milky Way of an obscuring cloud of very wide extent. This widespread cloud hides the

distant star-clouds in the middle of the Milky Way zone (Plate XXIII).

The luminous nebulæ and the obscuring clouds afford direct evidence that both gaseous matter and fine dust are very prevalent throughout the galactic regions. May it not be possible for extremely diffuse matter to be scattered throughout other parts of the Milky Way, where we see neither the luminous nor the dark clouds? It is possible to give a definite answer to this question, and the answer is in the affirmative. The evidence for this answer is provided in several different ways. We shall mention two only.

For the first of these we must anticipate somewhat the next chapter. In that chapter we show that our Galaxy or Milky Way system is but one of many millions of separate island universes scattered through space. These stellar systems are distributed more or less uniformly in all parts of the sky except those which are near to or within the region of the Milky Way. As we approach the Milky Way, the numbers begin to fall off, and within a zone which forms a continuous irregular belt along the Milky Way, of a normal width of from 10 to 20 degrees, not a single one can be found. The explanation is not that no island universes exist within such a zone, but that there is sufficient absorbing matter throughout the Milky Way region, even in directions where there is no apparent evidence of opaque clouds, completely to cut off their light from our view.

The second piece of evidence is provided by the stars themselves. When we analyse, by means of a

spectroscope, the light reaching us from the Sun, we see the band of prismatic colours crossed by numerous fine dark lines produced by the atoms of calcium, iron, titanium, etc., in the atmosphere of the Sun. But in addition to these lines, we see also other dark lines that are due to absorption by oxygen, nitrogen, water-vapour, etc., in our own atmosphere. There is a simple way by which we can distinguish between the absorptions that are present in the light when it leaves the Sun and the absorptions that occur during the passage of the light through the atmosphere of the Earth. It is only necessary to compare the light from the eastern edge of the Sun with the light from the western edge. As a result of the Sun's rotation, one edge is moving towards us and the other edge away from us. The wave-lengths of the lines in the spectrum of the light from the one limb are therefore slightly decreased and those in the spectrum of the light from the other limb are slightly increased. But the lines which originate in the Earth's atmosphere remain undisplaced and can therefore be distinguished.

A method identical in principle can be used to tell whether any lines in the spectrum of a star may be due to absorption by diffuse clouds of gas in interstellar space. We have seen how in the spectra of close twin stars the lines swing backwards and forwards because of the orbital motion. In 1904 Hartmann was observing the spectrum of Delta Orionis, one of the three stars in the belt of Orion. This star is a close twin star, one of the stars being much brighter than the other, so that we only see the spectrum of the brighter star. Hartmann

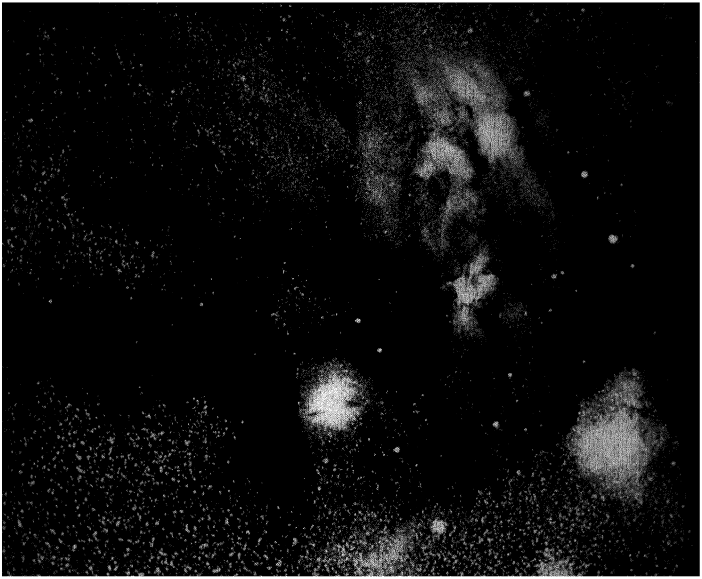


PLATE XXVIII.—NEBULOUS REGION IN OPHIUCHUS, SHOWING OPAQUE CLOUDS AND LUMINOUS NEBULOSITY.

(*a*) THE GLOBULAR CLUSTER, OMEGA CENTAURI.

(*b*) SPIRAL NEBULA, SEEN EDGEWISE-ON, IN THE CONSTELLATION OF BERENICE'S HAIR. NOTE THE ABSORBING BELT.

PLATE XXIX.

noticed that as the lines moved backwards and forwards whilst the star revolved in its orbit, there were certain lines due to calcium vapour that remained stationary. Such lines could not originate in the Earth's atmosphere and must therefore presumably originate in interstellar space.

Evidence has since accumulated that proves this beyond any possibility of doubt. We find, for instance, that the stationary lines are only seen in the spectra of stars at distances greater than about 1,000 light-years and that the more distant the star the stronger they are. The principal lines in the spectrum of a star which are produced by absorption in interstellar space are the lines of calcium and sodium vapour.

It is possible to make an estimate of the average density of this interstellar matter. The density proves to be so low that there are only about half a dozen atoms in every cubic inch. To appreciate how extremely small such a density is, we must realise that in the most perfect vacuum that the physicist can produce in the laboratory, with the aid of the most elaborate modern high-vacuum pumps, there still remain about 100,000 million atoms in every cubic inch. Another illustration is perhaps even more striking; if we throw a cup of water into the sea and let it mix thoroughly with the water of the oceans, and if we then draw out a cupful of sea water from any part of the sea, it will contain several dozen molecules of the water that was originally thrown into the sea.

The number of atoms in each cubic inch of interstellar space is small, but atom after atom takes its

toll from the light as it passes through, and at length, after it has travelled a distance of about 1,000 light-years, we are just able to detect the effect. The interstellar cloud of gas is not uniform in distribution; it pervades the whole of the galactic regions, but here and there it is strongly condensed, and where these condensations occur we say that there are nebulæ. The nebulæ are but the visible signs of all-pervading gaseous matter which for the most part we cannot see, though we can detect its effects.

The distances of some of the star-clouds in the Milky Way are measured by tens of thousands of light-years. We should like to obtain a more concrete idea of the actual dimensions of our galactic system and of the position in it that the Earth occupies. This is made possible by a group of objects of particular interest, called globular clusters. The name expresses accurately their appearance. Each cluster is a system, globular in shape, containing many thousands of stars; the stars are most densely clustered at the centre, the density decreasing from the centre outwards, at first rapidly and then more gradually. The appearance of a globular cluster is very much like the appearance of a target which has been shot at for a large number of rounds by a good marksman. The shots are thickly scattered within the bull's eye; in the inner they are less numerous; in and around the outer they are comparatively scarce. The brightest and nearest of the globular clusters is called Omega Centauri (Plate XXIX). To the naked eye it appears as a hazy star of the fourth magnitude; it was noted by Halley in 1677. Most of the clusters were observed by

Messier in the eighteenth century, though he knew them only as nebulosities. It was William Herschel and his son John who showed that they consisted of myriads of stars.

The progressive increase in the optical power of telescopes has revealed to the astronomer more stars, more nebulæ and more planets. But for the last half-century it has made practically no addition to the number of the star clusters. We may conclude that the reason is that there remain few, if any, still to be discovered. The distribution of the clusters is rather remarkable, for they are nearly all to be found in one hemisphere of the sky.

The distances of the globular clusters can be determined, because Cepheid pulsating stars are found to occur in them. They are all distant systems; the nearest clusters are Omega Centauri and 47 Tucanæ which are at a distance of about 18,000 light-years. The distances of other clusters range up to about 140,000 light-years. Knowing the distances, we can infer the sizes of the clusters; we find that they are fairly large systems, having diameters of the order of several hundred light-years.

When we map out the positions of the clusters, they are seen to form a flattened group, more or less symmetrically distributed with regard to the Milky Way. Our Sun is not centrally placed with respect to the group, but lies well out towards one side of it. This explains why most of the clusters appear to us to be in one half of the sky. The centre of the whole group is in the direction towards the constellation of Sagittarius and at a distance of about 32,000

light-years. It would seem not to be without significance that the centre of the group lies in the direction of the densest and brightest portion of the Milky Way, and we are tempted to infer that the centre of our galactic system is also the centre of the group of clusters. The greatest diameter of the system outlined by the globular clusters is somewhere about 150,000 light-years; the thickness of the system is from 25,000 to 40,000 light-years at its central portion, but is not so great in the neighbourhood of the Sun.

The galactic system formed by the star-clouds and gaseous nebulæ is probably coextensive with the system of the globular clusters, though it may be that the clusters extend out beyond the star-clouds. There is no doubt, however, that we must regard the clusters as belonging to our galactic system, and that the greatest dimension of this system is not less than 150,000 light-years.

Such a distance is the greatest of which we have so far had occasion to speak. If we reduce the scale so as to get a better appreciation of relative dimensions and represent 150,000 light-years by the diameter of the Earth—8,000 miles—then on the same scale the distance of the Earth from the Sun is only one-twentieth of an inch. The diameter of the Sun becomes only about three times the wave-length of light, so that the Sun is comparable in size to a microscopic dust particle.

We have another method, fortunately, by means of which we can get confirmatory evidence of the size of the galactic system. The flattened shape of this system suggests that it is in rotation; if it were

not rotating we might expect it to be globular. It is only within the last few years that the rotation has been detected. The rotation of the system must be controlled by the general gravitation of the whole system. The outer parts will therefore revolve more slowly than the inner parts, just as in the solar system the outer planets revolve more slowly than the inner planets, and as the outer parts of Saturn's rings rotate more slowly than the inner parts. This is different from the rotation of a rigid body such as a wheel, in which the outer parts revolve more rapidly than the inner parts.

If, then, we assume that the galactic system is in rotation, we shall expect to find that the stars lying between us and the centre of rotation are moving more rapidly than the Sun, and the stars more remote from the centre are moving more slowly. Superposed on the motion of the stars resulting from the rotation of the system there are, of course, the random motions of the individual stars. A statistical analysis of the mean motions of groups of stars in different parts of the sky is necessary in order to average out the random motions and to reveal the differential motion produced by the rotation. The greater the distance of the groups of stars from the Sun, the larger the differential motion will be. We do not make any assumption about how far away the centre of the rotation is, nor about its direction from the Sun.

The results of such a statistical analysis prove to be exactly in accordance with our expectation. The centre of the system indicated by this analysis is in the direction towards the dense star-clouds in Sagit-

tarius. It will be remembered that this was also the direction towards the centre of the globular clusters. But we can go further: we can get an estimate of the distance of the Sun from the centre of rotation and, since the rotation is controlled by the gravitation of the system as a whole, the total mass of the system can be deduced. The distance of the Sun from the centre proves to be about 32,000 light-years; this is in agreement with the estimated distance of the centre of the globular clusters and confirms the assumption which we previously made that the group of clusters could be supposed distributed haphazardly throughout the galactic system.

The controlling mass of the system proves to be about 160,000 million times the mass of the Sun. In this total mass is included the masses of all the stars, including any stars which may have ceased to shine and also the mass of the diffuse matter scattered throughout the system. We might think that the total mass of the interstellar gas, whose density is some thousands of millions of times smaller than the most perfect vacuum we can make, would not amount to very much. But when we make the computation we find that the total mass of this extremely rarefied gas is approximately equal to the total mass of all the stars. The mass of the Sun is about 2,000,000,000,000,000,000,000,000,000 tons; to write down the total mass of the interstellar gas in tons we start with the figure 1 or 2 and follow it with 38 zeros. The comparison between the total mass of this rarefied gas and the total mass of the stars is a striking commentary on the one hand on the great distances apart of the stars, and on the

other hand on the vast dimensions of our galactic system.

The time of one complete rotation in the neighbourhood of the Sun is about 225 million years. This may appear a slow rate of rotation, but the dimensions of the system are so great that the Sun has a motion through space, arising from the rotation, of 170 miles in a second. If we accept 3,000 million years as the probable age of the Earth, it follows that more than a dozen complete rotations have occurred during the lifetime of the Earth.

We have seen that the Sun occupies a very eccentric position in the galactic system. When the distribution of stars in the immediate neighbourhood of the Sun and out to a distance of about 1,000 light-years is investigated, a steady decrease in density of stars in all directions outwards from the Sun is found. It appears therefore that the Sun is situated in a localised cluster, which is probably a star-cloud similar to the star-clouds that are distributed throughout the Milky Way. This local cluster or star-cloud, like the larger galactic system of which it forms a part, is much flattened; its median plane does not lie exactly in the Milky Way but is tilted at a slight angle to the Milky Way. The diameter of this cluster is about 2,000 light-years; the Sun is about 300 light-years from its centre, which lies in the direction of the southern constellation of Carina.

The galactic system appears therefore to be a vast flattened rotating system extending over a distance of about 150,000 light-years, and containing many thousands of millions of stars sparsely scattered

throughout it. The distribution of the stars is far from uniform; there are numerous local aggregations or clouds of stars. Permeating the space between the stars is an extremely rarefied gas that in places reaches a higher density and is revealed to us either as luminous nebulous clouds or as opaque clouds. The total weight of this gas is comparable with the total weight of the stars. The Sun is situated in a somewhat eccentric position in a star-cloud that lies far out from the centre of the system. The stars are most closely aggregated around the central nucleus of the system, which lies in the dense star-clouds in Sagittarius.

A ray of light takes 8 minutes to come to us from the Sun. To cross from one end of the solar system to the other it takes 11 hours. To travel to the nearest star it takes 4 years. The journey across our local star-cloud takes 2,000 years ; that from the Sun to the centre of the galactic system takes some 32,000 years, whilst to travel from one end to the other of the whole galactic system something like 150,000 years is needed.

CHAPTER XI

CELESTIAL CATHERINE-WHEELS

THE bright green-coloured gaseous clouds and the dark absorbing clouds, considered in the last chapter, belong to our galactic system and occur exclusively in the Milky Way regions. There is another type of cloud or nebula, which does not show the characteristic green colour but appears white to the eye. The members of this group we may therefore denote for the present by the designation "white nebulæ." Sir William Huggins found in 1867 that the spectrum of a white nebula is entirely different from that of a green nebula. As we have seen, the spectrum of the latter consists of a number of isolated bright lines, which is the type of spectrum characteristic of glowing gas: the spectrum of a white nebula contains radiations of all colours, giving the prismatic band, crossed by dark lines, and bears more resemblance, therefore, to the spectra of the stars than to the spectra of the green nebulæ.

The green nebulæ are usually irregular in shape and outline, and many of them extend over large areas of the sky. The white nebulæ are for the most part fairly compact and regular in shape; they usually appear as faint patches of light, with a brighter but somewhat ill-defined nucleus at the centre. With a few exceptions, they are inconspicuous objects in the telescope and can best be studied by means of long-exposure photographs obtained with large telescopes. The largest and

brightest of the white nebulæ is known as the Great Nebula in Andromeda; it can be seen with the naked eye as a faint hazy patch of light (Plate XXXI).

The white nebulæ are far more numerous than the green and are found in all parts of the sky except in or near the Milky Way. Thus the white nebulæ and the green nebulæ are mutually exclusive. In and near the Milky Way, the green nebulæ only are to be found; outside these limits, the white nebulæ only are to be found.

These differences suggest that the two classes of nebulæ are entirely different in nature. In 1845, the discovery was made by Lord Rosse with his large 6-foot reflector that one of the white nebulæ, No. 51 in the catalogue by Messier, and hence known technically as Messier 51, had a definite spiral structure. This nebula, in the constellation of the Hunting Dogs, is now commonly known as the Whirlpool. Messier had described it as a double nebula, without stars; Sir John Herschel described it as a bright round nebula, surrounded by a halo or glory at a distance from it and accompanied by a companion. It is of interest to compare the drawings of this object by Herschel and Lord Rosse with one another, and with a modern photograph with a large telescope (Plate XXX). Though Herschel's drawing does not show any spiral structure, there are marked similarities between it and the photograph; the spiral structure is more pronounced in Lord Rosse's drawing than it really is, according to the photograph. It was also noted by Lord Rosse that on the finest nights the convolutions could be seen breaking up into stars. This appear-

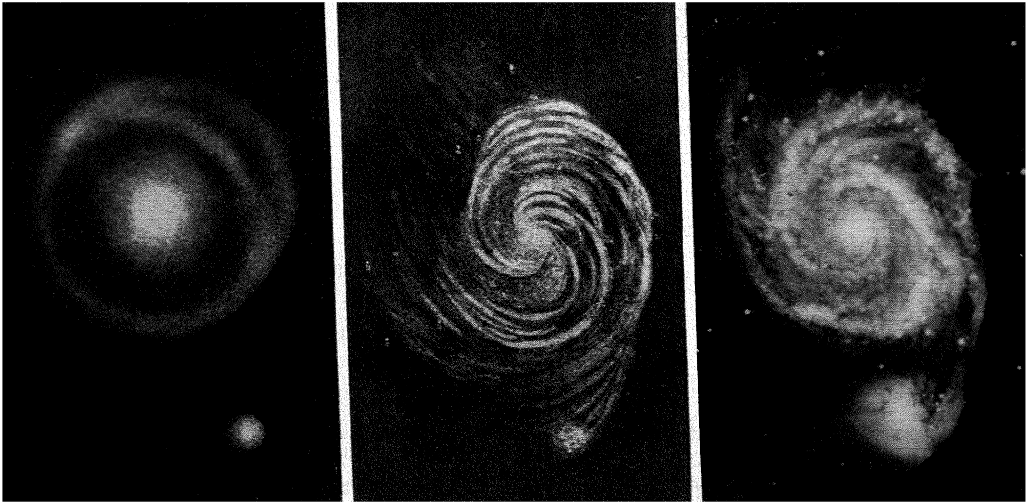
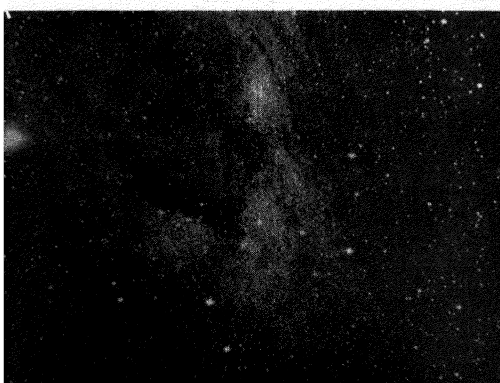


PLATE XXX.—THE "WHIRLPOOL" SPIRAL NEBULA, IN THE HUNTING DOGS.

(*a*) Sir John Herschel's drawing. (*b*) Lord Rosse's drawing. (*c*) Modern photograph by Ritchey.

(*a*) THE GREAT SPIRAL NEBULA IN ANDROMEDA.



(*b*) ENLARGEMENT OF SOUTHERN PORTION OF ANDROMEDA NEBULA.

PLATE XXXI.

ance is well shown in the photograph. The discovery of the spiral structure in the Whirlpool was followed by further discoveries of a similar type of structure in other white nebulæ. Such a definite structure is something quite different from the diffuse and formless green nebulæ.

When the spiral structure has once been realised, it is easy to recognise a similar structure in the Great Nebula in Andromeda (Plate XXXI). If the Whirlpool nebula is a flat system, that happens to be seen practically broadside-on, and we imagine it tilted through a considerable angle towards the edge-on position, we should expect it to appear somewhat like the Andromeda nebula. But though this nebula is easier to observe than the Whirlpool nebula, the fact that it is not seen broadside-on made the spiral structure more difficult to recognise.

We can find other white nebulæ, similar in their main features, inclined at all angles to the line of sight, from "broadside-on" to "edge-on." We may conclude from this continuous transition from one form to the other that a nebula, such as the one in the constellation of Berenice's Hair reproduced in Plate XXIX, is also a spiral system. The appearance of this nebula, seen edgewise-on, confirms our assumption that a nebula such as the Whirlpool is much flattened, having a far greater extension in the plane of the spiral arms than in the perpendicular direction.

The spiral structure is therefore not uncommon amongst the white nebulæ. They have the appearance of celestial Catherine-wheels, suggesting irresistibly that they are spinning round in space.

We naturally turn to the most favourably placed of these nebulæ, the Great Nebula in Andromeda, to endeavour to learn something more of the nature of these objects. It will be noticed that it has a bright diffuse nucleus and that the brightness of the spiral arms which extend outwards from the nucleus is far from uniform. The outer portions of the nebula, when photographed with powerful telescopes, are resolved into what appears to be a multitude of extremely faint stars. The doubts that were at first felt about the interpretation of these faint spots of light as images of stars have been completely removed by the careful investigations of Dr. Hubble at the Mount Wilson Observatory. By comparing large numbers of photographs with one another he has found that many of these bright points vary in brightness in a regular manner, and that the changes in brightness are of that particular type which we have learnt to be characteristic of pulsating stars: the fading from greatest to least brightness is slower than the subsequent brightening. These minute points of light must therefore be images of pulsating Cepheid stars. We found in Chapter IX that these pulsating stars are all giant stars of extremely high candle-power, many hundreds or thousands of times brighter than the Sun. In the Andromeda nebula, therefore, stars of high candle-power appear as faint spots of light which we can detect only with very powerful telescopes. A star in this nebula, of the moderate candle-power of the Sun, would not be detected as a star but would contribute its quota to the general faint unresolved luminosity. The obvious conclusion to be drawn is that the nebula is

at a very great distance from us. By determining the periods of pulsation of the Cepheid stars, we can find their intrinsic luminosities and therefore deduce the distance of the nebula. This proves to be about 870,000 light-years. The distance is much greater than the dimensions of our galactic system, and we are compelled to conclude that the Andromeda nebula is a system that lies far outside our galactic system.

This conclusion is somewhat startling and many astronomers were not at first prepared to accept it. Independent confirmation of the distance was much to be desired. This confirmation was provided by Dr. Hubble. He found that a particular star-image might appear on a few photographs only and be missing both on earlier and on later photographs. Many instances of these temporary images were detected. They suggested the flare-up of a new star in the nebula. By taking series of plates at short intervals, it was proved that the typical features of a nova outburst were present—the very rapid rise in brightness, followed by a slower and rather irregular decline. Now, though any one new star differs in many details from any other, we have seen that at greatest brightness their candle-power is always very high. If we assume that the average candle-power of the novæ which have been detected in the Andromeda nebula is the same as the average for the novæ in our galactic system, we have another means of estimating the distance of the nebula. This method is less precise than that based on the pulsating stars, but it is sufficient to provide a check. It is satisfactory to find that the distances derived by the two methods are in reasonably close agreement.

Knowing the distance of the nebula we can determine its actual size from measures of its angular dimensions. The only difficulty is to decide just where the limits of the nebula are. The brightness falls off rapidly towards its extremities and it appears that even photographs with long exposures do not show its full extension. By delicate observations of the brightness with a photo-electric cell, Professor Stebbins has recently shown that the brightness continues to fall off outside the limits recognisable on a photograph, until it merges into the background of the sky. The full extension of the nebula appears to be not less than 60,000 or 65,000 light-years. The conclusion is that the Andromeda nebula is a system which is of the same order of size as our own galactic system. The evidence indicates that it is a smaller system than our own. This conclusion is not necessarily final. The effect of the absorption of light by the diffuse gas throughout the Milky Way is to lead to a tendency to overestimate the dimensions of the system. During recent years, the revision of the dimensions determined for the galactic system has resulted in reducing our estimate of its size; the estimated size of the Andromeda nebula has been increased. We cannot regard the dimensions at present accepted for either system as necessarily final, and in the course of a few years their revision may still further reduce the present disparity.

It is indisputable, however, that the Andromeda nebula is to be regarded as a separate universe of stars, a universe which bears many strong resemblances to our own Universe. In Plate XXXI we reproduce an enlarged photograph of the southern

portion of the nebula. This bears remarkable similarity to many portions of the Milky Way: we see the localised aggregations of the stars into star-clouds and the presence both of luminous nebulosity and of dark clouds. The presence of luminous clouds of gas is proved by the appearance of bright lines in the spectra of some portions of the nebula.

In a spiral seen edgewise-on, such as is illustrated in Plate XXIX, the presence of a belt of absorbing matter lying in and near the central plane of the spiral is clearly shown. This is exactly analogous to the widespread belt of absorbing matter in and near the plane of the Milky Way, which causes the apparent division of the Milky Way into two branches through a great portion of its extent.

It is therefore with considerable justification that we can argue that our own galactic system is a spiral nebula. Situated as the Sun is, almost in the central plane of the system, we can only infer the spiral structure by analogy with many other systems which possess this structure. We should never have been able to guess it if we had seen no other spiral systems in the sky. But when we consider the similarity in size, when we note the presence of star-clouds, of luminous clouds of gas and of opaque clouds in the spiral nebulæ, and when we remember that our galactic system is flattened like the spiral nebulæ, we cannot deny that there is a strong resemblance. The spirals seen edgewise-on have exactly the flat grindstone structure that Herschel imagined for our own Universe.

Some of the spirals seem to have proceeded farther than others in the aggregation of the matter of

which they are composed into discrete stars. Some, such as the spiral Messier 81 in the Great Bear, shown in Plate XXXII, have stars in the outer portions of the arms only; in others, such as Messier 101, also in the Great Bear, star-clouds are found close to the nucleus.

In these photographs of spiral nebulæ it will be noticed that the stars are not distributed evenly along the arms, but that they tend to occur in localised clusterings. We have seen that the Sun is a member of a local cluster in our own Universe. To complete the analogy between the galactic system and the distant stellar universes, they also are found to be in slow rotation, and from the rate of rotation it can be inferred that the masses involved are many thousands of millions of times the mass of the Sun.

It is only in the nearer universes that we are able to detect individual stars. For the more distant systems, where this is no longer possible, we have no direct method of estimating the distances. But by making certain assumptions, we can get some idea of the distances.

The study of the nearer systems gives some justification for supposing that these stellar universes are generally similar to one another both in size and mass. We can make a rough estimate of the distances of the more remote systems if we assume either that they are all equal in size, or that they are all equal in total candle-power. It cannot be claimed that the distance of any particular universe derived on either assumption will be very accurate; we may expect, however, that the distances will be of the correct order of magnitude.

This conclusion is confirmed in a way that we shall now describe, which in turn leads to a method of determining the distances of even the faintest and most remote systems. We have explained how we can measure the velocity in miles per second with which a star is moving either towards or away from us, by means of the shift of the lines in its spectrum. The same method has been used for the spiral nebulæ and with surprising results. It is very rare in our galactic system to find a star moving faster than about 100 miles per second; the velocities of the spiral systems are much larger, usually amounting to many hundreds or thousands of miles per second. Not only have they these exceedingly large velocities, but they are all with one or two trivial exceptions moving away from us, and the farther the system is from us the faster it is receding. These results may be illustrated by the following figures for some of the distant universes. The first column gives the name of the constellation in which the system is to be found; the second column gives the distance estimated in the way described above; the third column gives

Constellation.	Distance (millions of light-years).	Velocity (miles per second).	Velocity/106.
Virgo	6	560	5
Pegasus	24	2,400	23
Cancer	29	3,000	28
Perseus	36	3,300	31
Coma	45	4,700	45
Ursa Major	72	7,400	70
Leo	104	12,200	115

the directly measured velocity. In the last column of the above table, we give the values of the velocities (in miles per second) divided by 106. If the figures in this column are compared with the figures in the second column, a close correspondence is seen. In comparing the figures, it must be remembered that the distances are based on the assumption that the various island universes are all equal in size. That the correlation between observed velocities and estimated distances is so close gives us considerable confidence in the validity of this assumption. We see now that we can accept the proportionality between velocity and distance and use it to infer the distance of any universe whose velocity has been measured. This provides the best method of estimating the distances of the very remote universes.

The greatest velocity yet measured is 24,300 miles a second for a remote nebula in the constellation of Boötes. We can infer that this nebula is at a distance of about 230 million light-years. This is the most remote system whose distance has been estimated. It is at such a great distance that the light by which it is photographed has been travelling through space for 230 million years. During this long journey the dinosaurs and flying reptiles have appeared on the Earth and with the slow march of evolution have disappeared again. Many of our mountain ranges have appeared, such as the Appa lachians, the Rocky Mountains, the Pyrenees and the Himalayas. And at length, when the journey was all but finished, man appeared on the Earth. Perhaps we can get a better picture of the length of this

journey if we change the time-scale and represent it by the three score years and ten of human life. On this time-scale, man has existed on the Earth for about 4 months; the Christian era has lasted for 5 hours only and the average span of human life is not more than about 10 minutes. It is only within the last minute or two that a telescope has been built sufficiently powerful to photograph this remote universe.

These stellar universes are to be seen in large numbers in all parts of the sky except where they are hidden from our sight by the opaque clouds in the Milky Way. It has been estimated that the 100-inch telescope of the Mount Wilson Observatory, by photographs with long exposure under good conditions, could show us somewhere about 75 million of these universes, if it could reach the whole of the sky and if the opaque clouds were not blocking out many of them from our sight. Up to the greatest distances to which this telescope can reach there is no evidence at all of any thinning out in the frequency with which these vast systems are scattered throughout space. Their distribution is approximately uniform in space, each system being on the average at a distance of somewhere about 2 million light-years from its nearest neighbour.

Astronomers are not content with the distances to which they have succeeded in exploring space and are anxious to reach out into the unknown beyond. So the great project of constructing a giant telescope, with a mirror 200 inches in diameter (twice the diameter of the largest hitherto made), has been conceived. The telescope is now under construction, but several years will be required for its completion.

Meanwhile we may pause to look at the position of the Earth in the Cosmos, as the astronomer now pictures it. The Earth is one of the smaller satellite bodies attendant upon the Sun, which is a dwarf star in a system containing many thousands of millions of stars. In this Universe the Sun has no pride of place, but lies far out from its centre, in one of the many clusterings of stars which pervade it. This Universe, of which we form so insignificant a part, is but one of many millions of universes that are generally similar to it. To what distances these universes extend we know not. All we can at present say is that out to the greatest distances, exceeding 200 million light-years, to which we have been able to explore, we have been unable to find any sign of an approach to the limits of this system. Each vast separate universe, held together by the force of gravitation, is spinning round in space like a gigantic Catherine-wheel, and it is to this rotation that the flat shape is due.

We have mentioned that the other universes or galaxies are all moving away from us, and the farther away they are the more rapidly they are receding. At first sight it might appear that the Universe in which we happen to find ourselves is the centre of the larger system, comprising all the universes, which we may term the Cosmos. But a moment's reflection will convince us that this is not so. The rate at which the distance from us of any system is changing is proportional to that distance; in other words, every distance is increasing at the same percentage rate. When one distance has doubled, all the other distances have doubled. But this indi-

cates merely a uniform expansion of the whole system. The distance between *any* two galaxies must increase at the same percentage rate. It follows that if we were to be placed in another galaxy we should observe the same phenomenon—that all the other galaxies were moving away from us. It is not a case of an aversion of all the other galaxies to our own particular galaxy, but an aversion of every galaxy to every other galaxy. This is what has been termed the expansion of the Cosmos.

The expansion is taking place at such a rate that every distance becomes doubled in about 1,300 million years. Long though this period is when judged by ordinary terrestrial standards, the expansion, when considered from the astronomical point of view, must be regarded as rapid. It implies that when the Earth was born, the separate universes were much closer together than they are at the present time; their mutual distances must all have been less than one-quarter of their present value. We are assuming that the expansion has been proceeding at a uniform rate throughout the life-history of the Earth, and this is an assumption which may not be justifiable. If we had been living on the Earth 3,000 million years ago we should certainly have had a much better view of the distant universes than we have at present; observations which now require a telescope with an aperture of 100 inches could then have been made with equal facility with a telescope with an aperture of only 24 inches.

It is not possible in a book of this nature to enter into a discussion of the theoretical implications of the observed recession of the universes. One view

which has been advanced supposes that originally the separate universes formed one system which at some instant exploded, the fragments scattering in all directions. If such an explosion occurred, some portions would have been shot off with higher speeds than others; but all the portions would continue to move outwards with their initial speeds, except in so far as these were modified by the mutual gravitational attraction. At any subsequent time we should find that each portion would have covered a distance exactly proportional to the speed with which it is moving. Wherever we might find ourselves in this exploded system, we should observe that every portion was apparently moving away from us, and we should have no means of identifying where the centre of the system was. We do not know, of course, what determined the "zero hour" at which the explosion took place, nor why every portion of the system was of about the same size.

Another suggestion which has been made is that it is only by chance that we happen to see the Cosmos expanding; it is possible that, just as some stars pulsate, so the whole Cosmos may pulsate, alternately expanding and contracting, going on endlessly through the same cycle. If we lived at some other time, either in the past or in the future, we might observe an apparent approach of all the other galaxies, which would have been even more difficult to explain than a recession. We can picture an explosion causing all the fragments to fly apart, but the supposition of scattered fragments all moving inwards at such a rate that they would come together at one point at the same instant appears much more artificial.

CHAPTER XII

THE AGE AND EVOLUTION OF THE STARS

IN the preceding chapters we have seen the great variety there is amongst the stars—in size, in average density, in surface temperature, in candle-power and to a much lesser degree in weight. We are tempted to enquire whether this variety is connected in any way with the ages of the stars and therefore with their evolution. If the stars were all of the same age should we find as great a variety as we do?

We are handicapped because we cannot see stellar evolution in progress, except in the one instance of the outburst of a new star, and we are not yet confident that every star must necessarily pass through this particular phase. The span of human life is but an instant in the lifetime even of our Earth.

We can endeavour to obtain guidance from theoretical considerations. If, for instance, a certain amount of matter is aggregated together to form a star, can we predict what its size and candle-power will be? We are at once face to face with the difficulty that we know nothing about the composition of the interior of a star. Observation tells us a great deal about the composition of the outer layer, which is the only portion that we can actually see. But can we necessarily assume that the composition of the matter deep in the interior of the stars is in any way similar to the composition of the outermost layer? Furthermore, we have no direct knowledge

of the state of the matter in the interior. Are we justified in assuming that a star is gaseous throughout? The pressure at a great depth in the star is enormous; it is possible that the central portions of the stars may be liquefied by the high pressure to which they are subjected. All that we can do is to make assumptions, which may or may not represent an approximation to the actual conditions; then to work out the consequences of these assumptions and see whether they are in agreement or in conflict with the results of observation.

Suppose we make the assumptions that the star is gaseous throughout and that the material everywhere has the properties, which we can study in the laboratory, of what is termed a "perfect gas." It is evident that the density, pressure and temperature will all increase continually from the surface of the star inwards to the centre. Calculation shows that, under these assumptions, the temperature within a star of the same size and of the same weight as the Sun must exceed one million degrees throughout the greater part of the interior and that at the centre it must be many millions of degrees.

This high internal temperature has two important consequences. In the first place it implies that we do not need to concern ourselves much about the composition of the material in the interior of the star. We have seen that by raising the temperature sufficiently we can split off one or more of the outer satellite electrons from the atoms. This process is called ionization. In the range of temperatures—a few thousand degrees only—available in the laboratory, we can merely knock off a few of the

outer electrons from some of the atoms. But when temperatures of millions of degrees are involved the ionization becomes enormously intensified. Practically all of the electrons are stripped from the atoms and we have a mixture of atomic nuclei and electrons. What we are really interested in, so far as the composition of the material is concerned, is the average weight of each particle. Suppose a star was composed entirely of oxygen; the atomic weight of oxygen is 16 and each atom is broken up into the nucleus and 8 electrons, making 9 particles in all, whose average weight is 16 divided by 9, i.e. 1·78. If it was composed entirely of iron, whose atomic weight is 56, each atom is broken up into the nucleus and 26 electrons and the average weight per particle is 2·07; if composed of gold, atomic weight 197, the average weight per particle becomes 2·46. Thus whatever the material of which the star is composed, with a single exception, we can assume an average weight per particle of 2, with the confidence that we shall not be much in error. The exception is hydrogen. The atomic weight of hydrogen is 1, and the hydrogen atom contains only one proton and one electron, so that for a star composed of hydrogen the average weight per particle is only $\frac{1}{2}$. We can therefore anticipate that the properties of a star will depend appreciably on the proportion of hydrogen which the star contains. It is sufficiently accurate to consider any star as composed of hydrogen, with weight per particle of $\frac{1}{2}$, and not-hydrogen, with weight per particle of approximately 2. This is a great simplification for the theoretical investigation of the interior of a star.

The second consequence of the high internal temperature is that it is not possible to neglect the pressure exerted by the radiation generated within the star as it endeavours to escape to the surface. It has long been known that any form of radiation, such as light, exerts a pressure upon any surface on which it falls. We have already had direct evidence of this pressure in the tail of a comet. The pressure exerted by the light from any terrestrial source is extremely small, though it has been possible to detect and to measure the pressure in the laboratory by delicate experiments. The pressure increases rapidly as the temperature of the source of radiation is increased; if the temperature is doubled the pressure increases sixteen-fold. At the extremely high temperatures within a star the pressure of radiation becomes very large. Thus, whereas if the temperature were 5,000° C. the pressure of the radiation would amount only to about one-twentieth of an ounce per square foot, at the temperature of 20 million degrees it is about 3 million tons per square inch.

We can now form a general idea of the state of affairs prevailing inside the star. The star is held together by its gravitation; were it not for the force of gravitation, the matter of which the star is composed would rapidly diffuse outwards and be scattered through space. Within the star the nuclei and electrons into which the atoms are split up are flying about in all directions, with velocities which are extremely great because of the high temperature. The electrons are speeding around with a velocity of about 10,000 miles a second; the heavier nuclei

of the atoms move more slowly, but with speeds up to several hundreds of miles a second. Atoms and electrons are continually colliding with one another. These numerous collisions are collectively equivalent to a pressure which is tending to disperse the material of the star outwards in all directions. Through this medley of hurrying atomic nuclei and electrons the radiation is attempting to escape. At the centre of the star, the radiation is of extremely short wave-length, comparable with the wave-length of X-rays. The free passage of the radiation is impeded by the atoms. The radiation is continually being captured by the atoms that it encounters in its path; the atoms retain the captured radiation for a short time and then re-emit it, generally in an entirely different direction. The radiation thus gradually buffets its way towards the surface of the star. The net effect of the absorption of radiation by the atoms and of its re-emission is equivalent to the pressure of radiation to which we have referred above, tending to drive the atoms outwards. We may compare the escaping radiation to a wind blowing outwards in all directions. The continual absorption and emission of radiation by the atoms gradually lengthens the wave-length of the radiation until, when it has reached the surface, it consists of the mixture of ultra-violet, visual and infra-red radiation with which we are familiar.

The mathematical investigation of these processes is one of great difficulty and has not been completely solved. There is the additional complication that we know little about the source whence the energy that the star continues to radiate is de-

rived: whether, for instance, the generation of energy occurs entirely or mainly in the hottest central region of the star, or whether it occurs more or less uniformly throughout the star. The method that has been used by Eddington, Milne and others is to assume that the star is built according to some particular model and to work out the consequences. Some of the results do not depend to a great extent upon what particular model is adopted, and we can therefore regard them as reasonably accurate.

It can be inferred that for a star of the size and mass of the Sun the temperature at the centre is about 20 million degrees. For the Sun and for stars of smaller mass, the effect of the pressure of radiation is relatively small compared with the gas pressure, i.e. the pressure arising from the motion of the atoms. But for stars of larger mass, the effect of the pressure of radiation becomes increasingly important and for such stars the central temperature is not so high. For the giant stars of large mass and large in size, the temperature at the centre is only one or two million degrees.

If the size of the star and the amount of matter in it are known, can we calculate its candle-power? We find that this is not possible without a knowledge of the average composition of the star. But we have seen that all the elements except hydrogen can be lumped together, being practically equivalent to one another when fully ionized. What we really require to know before we can calculate the candle-power of the star is therefore the percentage of hydrogen in the star. The candle-power is very

sensitive to this percentage; by varying the percentage of hydrogen in a star of the size and mass of the Sun, the candle-power can be varied in a range of 600 to 1. For a star of given weight and size, the candle-power is lowest when the star contains 85 per cent. by weight of hydrogen. If the percentage is greater, the candle-power is higher because the material of the star is less effective in damming back the escaping radiation; if the percentage is lower, there is more obstruction to the escape of the radiation, but the central temperature becomes so much higher that there is a greater net out-flow of radiation and consequently a higher candle-power.

We have no means of directly determining the percentage of hydrogen in the star. But we can proceed in the opposite direction and infer how much hydrogen the star contains by comparing the observed candle-power with the candle-powers computed by assuming several different percentages of hydrogen.

The observed and calculated candle-powers of the Sun can be brought into agreement for two values of the percentage content of hydrogen, one of which is lower than 85 per cent. and the other is higher. The two percentage contents which give agreement are 33 and 99·5. It is highly improbable that the Sun is nearly all hydrogen, as the latter figure would suggest, and we may therefore conclude that the Sun is about one-third part by weight hydrogen and two-thirds other substances.

It would seem that the majority of other stars must also contain about one-third hydrogen. With

this assumption we can calculate the candle-powers of stars of different weights. The candle-power for a given percentage content of hydrogen depends mainly upon the amount of matter which the star contains and only to a small extent upon its size. The computed relationship between candle-power and weight is closely satisfied by the actual data of observation. There must therefore be some cause which makes the hydrogen content practically the same for all stars, with few exceptions. What this cause may be is not known.

The massive stars have high candle-power; the stars of small mass have low candle-power.

The theoretical investigations are based upon the assumption that the material throughout the star is compressible like a perfect gas. This assumption is certainly reasonable for giant stars of low average density, such as Antares or Betelgeuse. But is it a reasonable assumption to make for the Sun, whose mean density is nearly $1\frac{1}{2}$ times the density of water? We know that water is practically incompressible. The molecules of a liquid are so close together that, however great the pressure we apply, we cannot squeeze them much closer together. With air or any other gas it is otherwise. The average distance apart of the molecules is much larger than the size of the molecules. Air is mainly empty space and by applying pressure we can force the molecules closer together.

When Sir Arthur Eddington first carried out these calculations, he anticipated that the observed and computed candle-powers would agree for the diffuse giant stars, but that there would be an increasing

divergence for stars of larger and larger mean density. His expectations were not realised; the agreement in the case of the giant stars was satisfactory, but, surprisingly enough, it was equally satisfactory for the dense stars. The only possible explanation is that these stars are also compressible like a perfect gas. How can matter much denser than water be as compressible as a gas?

The explanation, given by Sir Arthur Eddington, was simple and—when given—was obvious. Just as air in a room is mainly empty space, so also each molecule of the air is also mainly empty space. Sir Oliver Lodge compared an atom to Westminster Abbey, with a few gnats flying about in it. The Abbey represents the size of the atom, the gnats the electrons. Now conceive the walls of the Abbey removed, the gnats still flying about in the space which they had enclosed. We then have a fair picture of the emptiness of the atom, or of the molecule. Normally we can only compress a substance until the imaginary walls of the molecules are in contact with one another. Though we still have mainly emptiness, further compression is not possible. Liquids and solids are in this condition.

But in the star the imaginary walls which surrounded the atom have been demolished. The electrons (gnats) are no longer imprisoned within them but are free to mingle with the electrons of other atoms. There is now plenty of scope for further compression before the gnats begin to get jammed together. This will only occur when the density is of the order of 100,000 times that of water. It is therefore apparent that the matter in the Sun

and other similar stars is very far from the stage of maximum compression, and it is to be expected that the material will behave like a perfect gas, as indeed it does.

There are a few stars known whose candle-power is much lower than we should expect from the amount of matter which they contain. These are the stars which the astronomer has called the *white dwarfs*; the name was given because in general the white stars are giants. The small companion of Sirius is the typical white dwarf. We have seen that these stars have extremely high densities, and we can infer that the reason why their luminosities are low is that they have arrived at the stage at which the electrons and nuclei are jammed so closely together that the stellar material can no longer be considered as having the compressibility of a perfect gas.

"Dense matter," as matter at these extremely high densities has been called, has properties which are very different from the properties of normal matter. These properties have been investigated theoretically by Professor R. H. Fowler, with the aid of wave-mechanics. It is found from these theoretical considerations that compression cannot be continued until all the atoms are jammed closely together; there is a limit to which the compression can be carried. There comes a stage at which not more than a certain number of slowly moving particles can be crowded into a given volume. When this stage is reached, the only particles which can be squeezed in are the more rapidly moving particles. As the pressure increases the average energy in a

given volume therefore increases. But this energy is not available to be radiated away. It is only the excess of the total energy of motion of all the particles above the amount which is, as it were, tied up by this crowding together which is available for radiation. The rest is, as Sir Arthur Eddington has expressed it, kept on deposit. The final limit is reached when the whole of the energy is tied up on deposit by this crowding together and none at all can be spent. Thus, as the density increases, the energy available for radiation rapidly decreases and the candle-power of the star becomes progressively smaller. In the final stage the total energy is still great, but radiation of energy ceases and the temperature may therefore be said to be zero. When this stage is reached the star ceases to be visible and may then be termed a "black dwarf." The white dwarf stars are in a position intermediate between normal stars and black dwarf stars. We know only a small number of white dwarf stars; their luminosity is so low that it is only those which are in the neighbourhood of the Sun that we can discover. But it is probable that they are very abundant in space. Black dwarfs may also be abundant, but because they are invisible we have no hope of finding out anything about them.

In these investigations dealing with the interior of a star no assumptions have been made as to the origin of the radiation which the stars emit. We have mentioned (p. 129) that Lord Kelvin supposed that the Sun maintained its radiation by a gradual shrinkage and that the maximum lifetime possible on this hypothesis is about 25 million

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years. This estimate was quite inadequate for geologists. The study of the geological changes which the Earth has undergone forced them to the conclusion that the Earth must have existed for a much longer time than 25 million years. The phenomenon of radioactivity was not known in Lord Kelvin's day and the accurate method of determining the ages of certain rocks which radioactivity provides, as explained on p. 18, was not available. We have seen that the Earth must have existed for more than one thousand million years, and the age of the Sun cannot be less than that of the Earth. None of the sources of energy with which we are familiar in everyday life can account for an age of such length. We are forced to the conclusion that the Sun and the other stars can tap the enormous store of energy which is locked up in the atom.

The energy which is thus locked up is surprisingly large. If we could release it, we should from one ounce of coal obtain sufficient energy to run engines of a total horse-power of 100,000 for one year. In other words, the fuel requirements of a large generating station could be met by one ounce of coal per year. The *Queen Mary* could be driven across the Atlantic with the energy from a fragment of coal no larger than a pea.

According to modern physical conceptions, mass and energy are synonymous terms. The Sun is radiating energy into space at the rate of 62 horse-power from each square inch of its surface. The total energy which it emits is equivalent to a loss of weight of 4 million tons every second. Large as this loss is, the mass of the Sun is so great

(2,000,000,000,000,000,000,000,000,000 tons) that, if the radiation were maintained at its present rate, the Sun would last for about 16 million million years.

The equivalence of matter and energy can perhaps be better realised if we think of matter as composed of protons, carrying a positive electric charge, and electrons, carrying a negative charge. It is conceivable that if we could bring a proton and an electron together so that their charges coalesced and neutralised one another, both particles would disappear and a pulse of energy would remain. We have no evidence that this process does happen, nor even that it can happen in Nature. But if it can happen, the longest life possible for any star will be obtained on the assumption that the whole of the material of the star is ultimately transformed into energy.

The radiation does not take place at a uniform rate. The greater the mass of the star, the greater its candle-power or, in other words, the greater the rate at which it is dissipating its energy. The stars of large mass are very profligate of their resources; the star S Doradus, for instance, is losing more than one million million tons in weight every second. But as their capital gets smaller, they become less profligate and gradually reduce their rate of spending. Suppose a star to be formed with a very large initial mass; at first the mass will decrease at a rapid rate, but the rate will progressively slow down so that by the time the mass has become small the decrease has become very slow. The reason why there are few stars with masses exceeding twenty times the mass of the Sun is probably that the mas-

sive stars lose weight so rapidly that they soon cease to be massive stars.

However large the mass of the Sun may have been initially, it will have decreased to its present value in not more than 5 million million years, if it can be assumed that the Sun derives its energy from the actual annihilation of matter. But we have no proof of the validity of this assumption and it is doubtful whether it is correct. Theoretical considerations suggest that the annihilation of matter cannot occur at temperatures lower than some thousands of millions of degrees. The highest temperature in the interior of a star is about 20 million degrees. Such temperatures seem hopelessly inadequate for annihilation to take place.

There is an alternative process by which not all but a small fraction of the energy contained in matter can be liberated. This process is the building up of heavier atoms out of atoms of hydrogen. A helium atom, for instance, contains four protons and four electrons; the four protons and two of the electrons are bound together to form the nucleus, the two remaining electrons describing orbits around it. Since a hydrogen atom contains one proton and one electron, we can imagine a helium atom to be built up from four hydrogen atoms. But the weight of the helium atom is less than the weight of the four hydrogen atoms by about one part in 140. The weight which disappears when one helium atom is formed from the four hydrogen atoms is accounted for by the energy which is released in the process.

We can suppose also that the elements heavier than helium are built up in a similar way from

hydrogen atoms. The energy set free is then rather greater, though not appreciably greater, than in the building up of helium. The process of building up heavy atoms from lighter atoms such as helium may also be taking place; but the energy which can be obtained in this way is comparatively small. The mass of the oxygen atom, for instance, is only slightly greater than the combined mass of four helium atoms. We may say that approximately 1 per cent. of the mass of the star can disappear in the form of radiated energy, if heavier atoms are built up from hydrogen atoms, and if the star consisted initially entirely of hydrogen.

There are thus two conceivable alternatives: the complete annihilation of mass or its partial annihilation by the building up of heavy atoms. On either assumption, we may say that a star is able to continue to radiate light and heat by a process of self-cannibalism, slowly eating itself up. But the first assumption supposes that it can eat itself up completely; the second assumption requires that when only one-hundredth of the meal has been completed the star can go no further; it can no longer radiate, it is dead.

If we think of protons and electrons as the fundamental units of which matter is composed, we must suppose that the process of the building up of heavy atoms does occur. For these atoms exist and they must have been formed in some way. The interior of a star, where so far as we can tell temperatures higher than anywhere else in the Universe are to be found, would seem to be as favourable a place as any other that we can think of for this process to occur. Recently, the transmutation of elements has been

achieved in the laboratory. When atoms are bombarded by fast-moving particles—protons, electrons, or helium nuclei (called Alpha particles by the physicist)—the nuclei of some of the atoms are hit by the bombarding particles. The proton or Alpha particle may be captured by the nucleus and a new element is formed. Similar processes may occur inside a star, where the particles have very high velocities. The laboratory experiments make it probable that, at the temperatures which prevail in the interior of a star, the transmutation will proceed sufficiently fast to supply the energy required to maintain the star's output of radiation.

The possible length of life of a star is many hundreds of times longer, if annihilation of matter takes place, than it is if it does not. In the latter case the supply of fuel available for consumption is only about the one-hundredth part of the supply available in the former case. The star then has practically the same weight throughout its life; when 1 per cent. of the initial mass has been radiated away, it dies. But if annihilation of matter occurs, it will continue to radiate away its mass at a progressively slower and slower rate. The following table gives the duration of time required for successive changes of mass.

Mass (Sun = 1).	Duration (in millions of years).
very large to 35	38,000
35 „ 10	65,000
10 „ 3·7	214,000
3·7 „ 1·73	930,000
1·73 „ 0·92	5,210,000
0·92 „ 0·53	36,300,000
0·53 „ 0·31	281,000,000
0·31 „ 0·18	2,190,000,000

Thus, for instance, if the initial mass of a star was 0·92 of the mass of the Sun, about 36 million million years would be required for the mass to decrease to 0·53 of the mass of the Sun.

We have seen that the stars of high intrinsic brightness are the very massive stars and that there is a progressive decrease in intrinsic brightness with mass. If annihilation of matter occurs, we can interpret this as evidence of evolution; as the star grows older it loses weight and at the same time becomes gradually less luminous. But if annihilation does not occur, there can be no evolutionary significance in this relationship. A massive star is always a massive star; a star of small mass can never have had a large mass. It therefore makes a big difference to our ideas of the evolution of the stars whether or not we can suppose that annihilation of matter occurs inside the stars.

If annihilation does not occur, the possible age of the stars is limited to a few thousand million years. This time is comparable with the age of the Earth and would imply that the Earth is about as old as the stars. But if annihilation of matter does take place, the age of the stars can be extended to several million million years. We naturally look for evidence in favour of one or other of these ages. We find that the evidence is inconclusive; some evidence seems to point to the shorter age, other evidence to the longer age. One of the great unsolved problems of astronomy to-day is the decision between these two widely differing ages.

We shall consider briefly a few pieces of evidence. In our galactic system there are many thousands of

millions of stars. Some are heavy-weight stars, others are light-weight stars; some are moving fast, others slowly. Every star is attracting every other star in the system according to the law of gravitation and thereby tending to alter the speed with which it is moving. But the average distance of one star from another is so great that the attraction between two stars is in general extremely small. It might be thought that the velocity of any star would not appreciably be changed by the gravitation pulls of the other stars. On the other hand, it must be remembered that this interaction is taking place continuously, and the cumulative result over many millions of years may be far from negligible.

It is not possible to trace out the effect on any particular star, for the positions of all the stars are continually changing. But the general effect of the interactions of the stars one with another can be studied statistically by mathematics. It appears that the result of the mutual gravitational pulls is on the average to slow down the stars which have more than the average energy and to speed up those which have less than the average energy. If the interaction continues for a sufficient length of time, the average energy of the heavy-weight stars will become equal to the average energy of the medium-height stars and to the average energy of the light-height stars. We cannot and do not need to investigate what happens to any individual star. We group the stars, therefore, according to their weight, determine the average speeds of the stars in each group and compute the average energy for each weight-group. When we do this, we find that not

only are the light-weight stars moving considerably faster on the average than the heavy-weight stars, but also that the velocities differ by just the amount necessary to give approximately the same mean energy for each group.

Given the actual weights, speeds and average distance apart of the stars, it is merely a matter of mathematics to find how long the mutual interactions must have continued in order that this equal sharing out of energy will have resulted. The calculation gives a time of about 10 million million years. It would seem, therefore, that the stars must have existed for at least this length of time.

A second argument which points to the same conclusion is based on clusters of stars which have a common motion. The stars of the Great Bear, for instance, are moving together with the same speed through space; many other stars scattered over the sky, including Sirius, the brightest star, share this motion. Several other groups of stars that are moving together are known. As these groups of stars sweep onwards through the general system of the stars, the effect of the gravitational pull of all the surrounding stars is gradually to change both the speed and direction of motion of every star in the cluster. The effect will be most pronounced for the light-weight stars. After a sufficient time, therefore, the motion of the light-weight members of the cluster will have been changed to such an extent that we shall no longer be able to recognise them as members of the cluster. After a still longer time, the cluster will have lost the medium-weight stars and finally, after a further interval of time, the

motions of the heavy-weight stars will have been so distorted that the group of stars can no longer be identified as a cluster of stars with a common motion. We actually find that these clusters have lost their light-weight stars and most of their medium-weight stars, and the mathematical discussion of the problem indicates that several millions of millions of years must have elapsed for this to have come about.

A third argument of a more speculative nature supports the two preceding arguments. We have seen that the island universes scattered throughout space are of about the same size and the same weight. We can suppose that these have all gradually condensed from a primitive gas, scattered more or less uniformly throughout space. The time required for this to happen can be estimated and again indicates the long time-scale for the lifetime of the stars.

The principal argument against so long a life is based upon the observed recession of the distant Universes. We have seen that all distances become doubled in about 1,300 million years. If we work backwards in time, assuming the expansion to have been taking place uniformly in the past, we find that several thousand million years ago the Universes were collected more or less together. We can suppose that something in the nature of an explosion then took place and the fragments began to scatter outwards in all directions. But what preceded this explosive outburst we do not know, nor whether the stars and the galaxies existed as such. The Universe may have existed for an indefinitely long time in this sort of embryo state; but, if so, did the stars and galaxies exist? If they did, were the galaxies more

compressed than they are now? May not the expansion of the Cosmos have been accompanied also by an expansion of individual galaxies?

These are questions that we cannot answer, to which perhaps no answer will ever be forthcoming. That it is necessary to ask them makes us feel somewhat insecure about our previous arguments in favour of an age for the stars much greater than the few thousand million years since the galaxies were collected together. The stars were then possibly much closer together than they are now. Their mutual gravitation pulls would in that case have been much larger and the equal sharing out of energy amongst the stars would have been more rapid; it may have been practically complete by the time the dispersal of the system took place. The same considerations apply to the moving clusters. We do not know how or when these came into being. But we must suppose that they existed when the separate Universes of to-day were collected together; they may have been practically in their present state and have lost their light-weight stars before the initial explosion. The argument based upon the condensation of galaxies from a primitive gas scattered through space would seem also to fall to the ground.

A possible means of escape from these difficulties is perhaps to be found in the suggestion which has been made that the recession of the galaxies is not permanent but that the Cosmos may be in a state of pulsation, alternately expanding and contracting. It would then be just a matter of chance that we happen to exist at a time when expansion is taking place.

The pulsating Universe is *mathematically* possible according to the theory of relativity. There are great difficulties in making it work in detail, but these are perhaps not insuperable. It would appear to provide a loophole by which we can fit in the long time-scale, which the stars seem to demand, with the present observed rapid expansion of the Universe. On the other hand, our arguments in favour of the long time-scale have implicitly assumed that the interactions of the stars have taken place throughout their past history at the same rate as at the present time. We cannot now feel at all certain that this assumption is justifiable.

Thus, whereas a few years ago astronomers had a theory of stellar evolution that seemed to be self-consistent, with an age for the stars of several millions of millions of years, everything is now in the melting-pot. It frequently happens in scientific investigation that a new discovery cannot be fitted in with accepted theories; the theories have then to be recast or, if necessary, abandoned and a new theory formulated that will embrace the new discovery. That is how progress in science is made. It is the discovery of the recession of the galaxies and the expansion of space that has called for some revision of the ideas of stellar evolution recently current. But at present we are not certain what we must give up and what can be retained.

We can outline two tentative theories of stellar evolution according to whether we do or do not assume that annihilation of matter is occurring within the stars. If we assume this, we suppose the star to start as a tenuous condensation in a mass of

nebulosity. The star will be large in size and of low mean density, somewhat like the giant red stars such as Antares. At first the diffuse gaseous mass will contract rapidly under the action of gravitation. The contraction will release gravitational energy, causing an increase in the central temperature; at the same time energy may also be released by the synthesis of more complex elements from hydrogen. The output of radiation from the star will remain practically steady, but the surface temperature will rise; the increased radiation from each square foot of the surface, due to the rising temperature, will approximately counterbalance the decrease in surface area due to the contraction. The star will pass rapidly from a red giant star to a blue giant star. During this stage there is very little decrease in the mass of the star. When the central temperature has risen to about 20 million degrees we must suppose that the annihilation of matter commences. There is no further contraction and the whole of the energy which the star now radiates is at the expense of its mass. The star now slowly radiates away its mass; the decrease in mass is accompanied by decrease in luminosity. The central temperature remains constant, but the surface temperature slowly decreases, and the star passes through the successive stages from a giant blue star to a dwarf yellow star and then a dwarf red star. The complete time for the transition from a giant red star to a giant blue star and then to a dwarf red star may occupy several hundred millions of millions of years.

If we do not accept annihilation of matter as pos-

sible, we must draw a different picture. The synthesis of heavier elements from hydrogen will now provide the main source of energy within the star. We suppose, as before, that in the early stages of the evolution there is rapid contraction of the large diffuse gaseous mass. The central temperature rises rapidly until it becomes sufficiently high for the synthesis of heavier elements from hydrogen to become possible. This process then provides the main source of energy. The star continues to draw on this supply of energy, the mass and also the luminosity remaining approximately steady. When this source of energy begins to fail, contraction must again set in and the mean density will rapidly increase. At length the material at the centre of the star will become so dense that the gas laws are no longer obeyed. The star will gradually pass into the white dwarf stage with rapid decrease both in size and in output of radiation. In this stage of the evolution instability may set in; the star may suddenly collapse, with the rapid release of a large amount of gravitational energy. The star has become a nova. The nova stage is succeeded by the white dwarf stage, which is succeeded by the black dwarf stage. The complete time for this sequence of changes to occur will be a few thousand million years.

At the present time, the balance of evidence would seem to be in favour of the second picture, but a definite decision between the two will probably have to await some further knowledge as to the processes by which energy is generated in the interiors of the stars.

CHAPTER XIII

WHAT WAS—WHAT IS TO BE

IN the preceding chapters we have been concerned mainly with the results of observations of various sorts and with the conclusions which can be drawn from them. We have been building on fairly sure foundations. Some of the conclusions are admittedly tentative because our information is incomplete. We are still in ignorance, for instance, of the source of energy within the stars and whether the energy is generated in a limited region near the centre of a star or more or less uniformly throughout the star as a whole. In this chapter our foundations are much less secure; we shall attempt briefly to envisage what was the past of the Universe and what will be its destiny. We can expect little help in such matters from observation; we must rely instead mainly on inference. It must therefore be emphasised that we are entering the uncertain regions of speculation.

We have found that in the Universe as a whole, matter is largely aggregated into vast discoidal systems or galaxies. Each of these systems has a weight many millions of times the weight of the Sun; each is in slow rotation. In any single system we find both diffuse clouds of gas and stars; but whereas some systems appear to be almost entirely clouds of gas, others appear to consist largely of stars. There is great variety amongst the stars except in one respect—their weight. With few excep-

tions, the weight of any star is not greatly different from the weight of the Sun. It would seem that these uniformities must have been due to the operation of similar processes throughout the Universe.

If, at the present time, the whole of the matter in the Universe was spread out uniformly, space would appear extremely empty. One cubic inch of ordinary air would occupy a vast volume of about 6 million million cubic miles. As a result of the recession of the galaxies, the average density of matter in space is becoming steadily less. A few thousand million years ago the average density may have been about one thousand times greater than at the present time; even so, the average density was extremely low, judged by any terrestrial standards.

We may suppose that there was a time when the matter in the Universe was distributed uniformly throughout space as a diffuse gas of extremely low density. We do not know and we cannot prove that this was so; but the supposition provides a model and we can examine the consequences.

If the density had been absolutely uniform the system might have existed in this condition indefinitely. But if the density was slightly greater in some parts than in others, there would be a tendency for condensations of matter to grow in the regions where the density was above the average. Any slight disturbance which upset the supposed initial uniform density would give the force of gravitation the opportunity to get to work; provided the disturbance was sufficiently large, gravitation would overcome the tendency of the atoms to diffuse from the regions of greater density to the regions of lesser

density and thus to restore the conditions of uniform density. Any condensation which was of sufficient size to begin with would gradually grow; the small ones would be smoothed out again. Corresponding to any given initial density, there is a definite minimum weight necessary in order that a condensation may grow. The lower the initial density, the greater the weight that the condensation must have in order that gravitation can overcome the natural tendency of the condensation to disperse.

We can therefore make an estimate of the minimum weight of any condensation that could have formed out of the uniformly distributed gas which we have conjectured. The estimate cannot be very precise, because we do not know what the composition of the gas was; the average speed of the atoms depends upon this composition and the minimum weight of a condensation depends in turn upon this average speed. We are able, nevertheless, to conclude that the minimum weight must have been many millions of times the weight of the Sun. The condensations could not have been stars, but must have been systems comparable, in the amount of matter which they contain, with the spiral nebulæ.

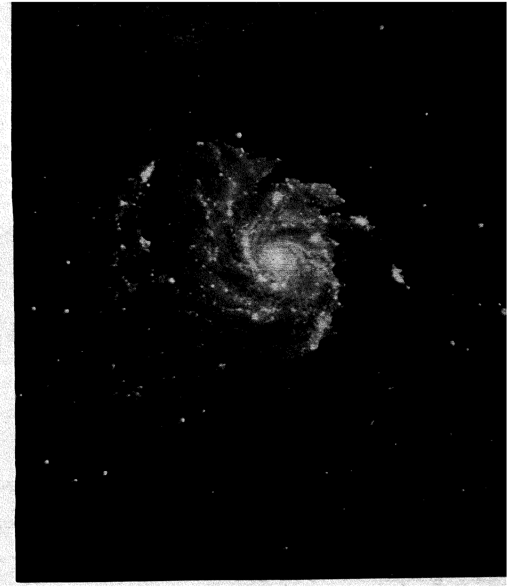
Each condensation as it formed would be likely to have a certain amount of spin, for it would be difficult to initiate any disturbance in our hypothetical primæval gas without causing differences of motion between different parts that would introduce rotations. As each nebulous condensation gradually contracted, its rate of spin would increase, in accordance with a well-known dynamical law, so as to keep the angular momentum constant. As

the rate of spin gradually increased, the system would first become slightly flattened, somewhat like Jupiter; a bulge would next form round the equator and become more pronounced until the system assumed a lenticular shape; after this, with still increasing spin there would be no further flattening but matter would be ejected through the sharp equatorial edge into the equatorial plane. If the nebula was absolutely symmetrical, the ejection of matter would occur all round the equatorial edge. But any slight disturbance, such as the gravitational attraction of an adjacent system, would be sufficient to introduce a bias and to cause the matter to be ejected from two diametrically opposite points.

Although we cannot prove that the spiral nebulæ have been formed in the way we have conjectured, we do in fact find systems of all the shapes which according to theory a rotating contracting mass of gas would pass through in succession—spherical, oblate, lenticular—and systems in which matter appears to be streaming from opposite ends of a diameter.

The nebula formed in this way is initially of very low density. As it contracts the mean density increases considerably. The average density of the material in the spiral nebulæ as we now see them is such that one cubic inch of ordinary air would occupy a volume of several thousand cubic miles. This density is many times greater than the density of the primæval gas; it follows that the condensations which can form out of it are much smaller in mass. The greater density gives gravitation a much better chance. We find that in such a nebula gravitation

(*a*) The Spiral Nebula, Messier 81, in the Great Bear.



(*b*) The Spiral Nebula, Messier 101, in the Great Bear.

Plate XXXII.

can hold together a condensation comparable in weight with the Sun. It seems reasonable to suppose that the stars have in fact been born in this way—by condensing out of the nebulous clouds in the separate universes. This may have occurred in two stages, for the photographs of nebulæ such as that in the Great Bear (Plate XXXII) show a tendency for the stars to be aggregated into large clusters. We have seen that the Sun is a member of a localised cluster in our galactic system. It is probable that as a nebula contracts it breaks up first into a number of relatively large condensations and that each of these in turn breaks up into groups of stars. This does not exclude the possibility of smaller condensations forming directly in the nebula and giving birth to individual stars.

In this way, starting with an initial distribution of gaseous matter of extremely low density, we have three successive stages—first the formation of large systems weighing many millions of times more than the Sun, which we identify with the great extragalactic nebulæ; then the formation of localised clusterings within each nebula and finally the break-up of these clusterings into individual stars, comparable in weight to the Sun.

Many of the stars are twin systems, as we have seen in Chapter IX. How have these been formed? We can suppose the same process to have continued after the individual stars were born. The rotation that has been generated cannot disappear: it must persist. We can suppose that, as a general rule, each star when it was born was rotating. We know that our own Sun is rotating and we have direct

evidence of the rotation of many other stars. Some stars are rotating so rapidly that the rotational speed at the equator is 200 or 300 miles a second. As the star contracts after its birth, its rate of rotation will increase; the star may assume a flattened lenticular shape and at length eject matter from the equatorial edge. But it can be shown that this ejected matter would not condense into nuclei—such as smaller stars or planets. It would either be gradually dissipated away into space or it would form a nebulous atmosphere about the stars. Many stars with nebulous atmospheres are known and they may have been formed in this way.

But the evolution of the star may not necessarily take place as we have supposed; it will only do so if the star is much condensed towards the centre. If this is not the case, evolution follows a different course. The initial spherical mass of gas will become flattened as it contracts and its spin increases; then, as the spin still further increases, it will become considerably elongated and a neck will begin to form in the middle, the mass concentrating towards the two ends. The neck will become deeper and deeper until at length the body will divide into two separate portions, rotating about each other practically in contact. Many of the eclipsing twin systems seem to be in this stage.

The evolution will not end here. After the cleavage into two bodies has occurred, they will both continue to contract and to spin at a faster rate. Each star will raise large tidal protuberances on the other. The period of rotation of each star will be shorter than the period of mutual revolution of the

stars about each other. The tidal protuberance on either star, as it moves around the star under the gravitational attraction of the other star, will exert a braking action, which will tend gradually to equalise the periods of rotation of the two stars and the period of mutual revolution. During this process the stars will gradually separate and the period of revolution will increase.

There are limits, however, to the extent to which this evolution can proceed. It can be shown mathematically that the separation of the two stars and the period of revolution will only increase to a limited extent. The twin-stars of wide separation and of long period certainly cannot have been formed in the way we have described. We must attribute the existence of such systems to an entirely different process. We can conceive of two processes by which these systems of two widely separated stars with a long period of revolution may have been formed. In the first place, it is possible that two adjacent nuclei in the original nebula condensed out sufficiently close to one another to be held prisoners, the one to the other, by their mutual gravitational pull; they would have fallen together but for their relative motion, and the result was that each revolved about their mutual centre of gravity. We should expect that the distance between two separate condensations would be much greater than the distance between the two components in a system formed by the cleavage of a single star.

In the second place, it may have happened that two stars which had condensed from separate nuclei chanced, as they sped along, to pass each other so

closely that they became bound to one another and henceforth had to follow a common existence as a twin system. The probability of this happening would depend upon the average distance apart of nuclei at the time they condensed out of the original nebula.

We can thus form reasonable hypotheses to account both for the systems which consist of two stars nearly in contact revolving rapidly about each other, and for the systems which consist of two stars widely separated from each other and with long periods of revolution.

The examination of the sequence of events which may be expected on purely theoretical grounds to follow from the evolution of a primordial diffuse nebula has led to a plausible explanation of many of the formations which we see in the heavens. But it has not suggested as a possible by-product a system in any way comparable to the solar system, consisting of a Sun surrounded by a family of planets. It is not possible in the limits of this book to attempt to give an account of the various theories which have been suggested to account for the existence of the solar system. There are fatal objections to every theory which supposes the Sun to have been alone in space: for a plausible theory we must suppose another body to have passed near to the Sun.

We shall consider therefore the sequence of events which may be expected to have happened on the hypothesis that another star passed near the Sun, but not so closely that the two bodies became bound to each other by their mutual gravitational pull. As the star approached, its gravitational pull raised

a large tide upon the Sun, causing a protuberance or hump to form, pointing in the direction towards the oncoming star. As the star drew still nearer this hump grew to such an extent that a long tongue of matter was drawn out from the Sun. When the star was at its nearest, the rate of ejection of matter from the Sun was greatest; then, as the star passed by and its distance from the Sun increased, the ejection gradually diminished. The tongue of matter at length broke off from the tidal hump, which slowly subsided as the disturbance passed away. A cigar-shaped tongue of matter remained as evidence of the passage of the stranger star. The ejected matter rapidly cooled, and after a comparatively short time liquefaction set in near the two ends. A break-up into detached masses followed. The smallest masses would form out of the densest matter, and it is in accordance with expectation that we find the largest planets, Jupiter and Saturn, in the middle of the series and smaller planets on either side. The smaller planets were probably liquid or solid from birth; the two largest planets may have been initially gaseous.

The tidal forces exerted on the planets by the Sun—the central mass—gave rise in a somewhat similar way to the further ejection of matter from the planets and the formation of satellites.

In the way which we have briefly outlined we can give a logical explanation of the formation of the solar system and of its principal features. The main argument against the theory is that the probability of two stars approaching sufficiently close for a tongue of matter to be ejected is extremely

small. We can calculate from the present average distance apart of the stars in the neighbourhood of the Sun how often this is likely to happen. It is found that it is unlikely for it to occur more than once in several million years. This would seem to suggest that the solar system is something exceptional in the stellar universe and that in our galactic system there are not likely to be more than a few stars surrounded by systems of planets. Whereas the Earth was once believed to be the centre of the Universe, we now are apt to regard with suspicion any theory which makes it appear as something exceptional or as occupying some privileged position in the Universe. But we are forced to admit that no more plausible theory has been suggested, and improbability is not by itself a sufficient ground for rejecting it. A possible avenue of escape from this one objection may be provided by the expansion of the Cosmos. We put the age of the Earth at a few thousand million years. If we go back that distance in time, we find the separate universes much closer together than they are now The average distance apart of the stars may also have been appreciably less than at the present time. Though we cannot be sure of this, it suggests that planetary systems may be much more common than was formerly thought.

We have sketched out what seems to be the probable course of evolution of the Cosmos, if we can assume that it started from a uniform distribution of matter in the form of an all-pervading gas of extremely low density. The questions may be asked: What preceded this uniform distribution of matter? How did it come into existence? Was a definite

act of creation involved? I do not pretend to be able to give any answer to these questions. To assert that the Universe may have existed in this initial state for countless ages is only shelving the question or to adopt the picture suggested by Sir James Jeans "of the finger of God agitating the ether" is merely a confession of ignorance. Astronomy cannot take us any farther back in time. I am writing as an astronomer, not as a metaphysician or as a theologian, and I prefer therefore to leave these questions unanswered.

We have looked backwards in time as far as we are able. Looking forwards, we ask the questions: Whither is the Universe bound? What will be its end? Before attempting to answer these questions about the Universe, we shall start at home and consider what fate there may be in store for the Earth and for Mankind. We can picture two possible ends, depending upon what we consider to be the normal course of stellar evolution. These two possibilities are a slow death by cold or a quick death by heat. The Sun is consuming its substance at the rate of four million tons every second; as its reserves of fuel get less and less the Sun will gradually get cooler, its output of light and heat will slowly decrease. The conditions for life on the Earth are directly dependent upon the radiation which the Earth receives from the Sun. The Earth has no store of heat of its own; as the Sun slowly cools down the Earth will gradually get colder and colder. How long it may be before the average temperature has dropped so much that human life is no longer possible depends upon how great is the store of fuel

upon which the Sun has to draw: in other words, upon whether its energy is derived from the annihilation of matter or from the building up of complex elements from hydrogen. If annihilation of matter provides the main source of the radiation, then in one million million years' time the Sun will only have lost about 6 per cent. of its weight. The Earth will be a little colder than it is now and life a little less bearable. The face of the Earth will have changed considerably; erosion will have levelled the mountains with which we are now familiar, many thousands of millions of tons of material will have been deposited on the ocean floors and this extensive redistribution of the weight of the surface materials may have upset the equilibrium of the Earth's crust and brought about the uplift of new mountain masses. The oceans will have largely turned to ice, and a permanent and universal ice age will be slowly but inevitably in course of development. The changes will be so slow that human life will doubtless adapt itself to the gradually changing conditions, and we can conceive of its possible existence for many millions of millions of years. But at length the inevitable would happen; life must succumb to the gradually increasing grip of the cold as the Sun gradually passes into its long-drawn-out old age, with but a shadow of its former glory and but a fraction of its present weight.

Our previous discussion has suggested that it is more probable that annihilation of matter does not take place and that the energy radiated by the Sun is provided by the building up of complex elements from hydrogen. As the Sun now contains about

one-third part by weight of hydrogen, the maximum possible loss of weight is limited to about one-third of 1 per cent. For somewhere about 40 to 50 thousand million years the Sun could continue to radiate at a rate not differing very greatly from its present rate; during this period the temperature of the Earth would not greatly change. But after this period most of the hydrogen will have been converted into heavier elements; the supply of fuel necessary to provide the energy for radiation will be rapidly failing and the Sun will then begin to shrink and its output of heat to decrease. There will be a relatively rapid fall of temperature on the Earth and life would probably very soon become extinct. This would not happen for several thousands of millions of years; but as the Earth is already a few thousand million years old, it follows that, on this hypothesis, the Earth has lived more than an insignificant fraction of its life. If we think of the whole lifetime of the Earth as changed in time-scale so as to equal the normal span of human life, on our previous assumption the Earth is still a new-born infant an hour or so old, but on the second assumption it is a child of a few years.

There remains another possibility—that the Sun may pass into the nova stage. We do not know what is the cause of a nova outburst; but we have seen that there are reasons for supposing that it is a stage in stellar evolution which every star may have to pass through. We know, moreover, that our Sun has not yet passed through it. So far as we can tell, when the Sun is ripe for this catastrophe we shall have little, if any, preliminary warning. In the

course of a few days or even of a few hours its output of heat would increase to such an extent that all life would become extinct; the oceans would be turned into vapour; trees, forests, cities and everything combustible would be burnt; the Sun would rapidly swell and might even consume and swallow up the Earth. It is therefore possible that the Earth will not survive to its old age but that it may be cut off while still in the prime of life.

We have sketched out a scheme of evolution starting with a uniformly distributed primæval nebula. The individual universes have been formed by condensation from this nebula, and the stars in their turn have been formed by condensation out of these universes. In the attempt to trace out the course of evolution of individual stars we have encountered the difficulty that we are uncertain as to the source of the supply of energy which is needed to enable a star to continue to radiate. But whatever the source of energy may be, it is inevitable that sooner or later the supply will be exhausted and the star will cease to send out radiation. The radiation is at the expense of the weight of the star; each individual star continually loses weight and the emitted radiation is accumulating in space. The radiation travels on and on through space unchanged, except when it encounters interstellar matter, in the form of atoms, electrons or small dust particles. The effect of these encounters is gradually to increase the wave-length of the radiation, so that ultimately it will all be transformed into waves of very long wave-length, essentially similar to extremely long radio waves.

It has been suggested that there may be a converse process taking place in interstellar space and that the radiation may there be re-formed into electrons and protons; in other words, that matter may be re-created out of energy and an all-pervading nebulosity thus produced anew, which could go through the same process of evolution. But it is not easy to understand how birth could be given to matter in the way supposed. It runs counter to all our experience, summed up in the famous "Second Law of Thermodynamics."

The science of thermodynamics is concerned with the various forms of energy and the changes which they can undergo. It is based on two laws. The first law states that the total energy in the Universe is constant; energy can neither be created nor destroyed. This is the principle of conservation of energy. When this law was formulated the equivalence of mass and energy was not realised and it was also believed that matter could neither be created nor destroyed—expressed in the principle of conservation of matter. The original form of the law must be widened to include matter, so that we now have the principle of the conservation of matter and energy jointly.

The second law of thermodynamics is concerned with the availability of energy and can be crudely expressed in the form that energy continually becomes less and less available, or, in other words, that there is a progressive degradation of energy. For example, in any heat engine we must supply more heat energy than we can recover from the engine in the form of work; a proportion of the energy is lost

for practical purposes in the condenser of the engine. It is dissipated in the form of increased random motion of the molecules, which we recognise as heat. When heat flows from a hot body to a cooler body there has been a net loss in the availability of energy; so also when light-energy is changed into heat-energy or radiation of short wave-length into radiation of long wave-length. All these processes change the form of the energy, in that they degrade it or make it less available for co-ordinated or organised purposes. Another manner of expressing the law is that there is a progressive decrease in the amount of organisation in the Universe. Energy becomes more and more disorganised.

The second law of thermodynamics is a law based upon experience; we accept it because we have never found it to be violated. It teaches us that processes in nature tend to be uni-directional. We cannot reverse them, except by the expenditure of organised energy. Water will run downhill; the energy which it gains by running downhill can be utilised, as in hydro-electric power schemes. We could use the energy so obtained to lift the water uphill again but we should find that we should not be able to lift as much water as had run down. Some of the energy has been converted into forms that are not available. Every process of any sort that takes place increases the total amount of disorganisation.

Thus it seems that the end of the Universe must come when all the energy has been degraded to such an extent that it has reached the lowest possible

state of availability. Disorganisation is then at its maximum. The total amount of energy in the Universe is the same as it was initially, but all capacity for change has been lost. There will then be thermodynamic equilibrium throughout the Universe; this state has been described as the " heat death " of the Universe.

There seems to be only one possible means of escape from these conclusions. The second law of thermodynamics is a law based upon experience in a Universe which is expanding. From the scientific point of view the background conditions, relative to which we must measure the degree of disorganisation, are changing. It has been suggested that this expansion may not be permanent; that the Universe may really be pulsating and that it is only by chance that we happen to exist at a time when it is expanding; and that in a contracting universe organisation may increase and energy become increasingly more available. A scheme of relativistic thermodynamics has been formulated by Professor Tolman which requires that this should be the normal condition in a contracting universe; the re-formation of matter out of radiation would then be possible. We can thus conceive the Universe to pass through a series of successive stages, first of running down and then of being wound up again; we need not think of any beginning or of any ending to such a universe.

From the strictly scientific view-point we can therefore no longer dogmatically assert that the heat-death of the Universe at some finite time in the future is necessarily required by the laws of thermo-

dynamics. In the present condition of knowledge, we are free to consider it equally possible either that the Universe is slowly but inexorably pursuing its course towards old age and inevitable death, or that it is destined to undergo periodic rejuvenation and to live its life over and over again. Sir Arthur Eddington regards the second alternative as " wholly retrograde "; he has expressed himself to be an evolutionist not a multiplicationist. Sir James Jeans takes the same attitude: " It is hard to see what advantage could accrue from an eternal reiteration of the same theme." But there are many others who find the doctrine of the heat-death of the Universe equally repugnant. To such it may be a consolation to reflect that in the present state of knowledge it is not possible to claim that this doctrine has been definitely established. As a practical astronomer, I must emphasise that these are at present realms of speculation. Observation is the touchstone of every theory or hypothesis in science; the two alternative but divergent theories as to the future of the Universe cannot yet be tested by astronomical observations. Until this is possible, we are free to select whichever we prefer.

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